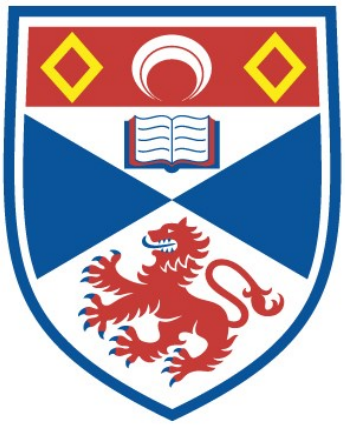
EXPERIMENTAL AND PETROLOGICAL INVESTIGATIONS OF SOME MAGMATIC PHENOMENA

Peter John Wyllie

A Thesis Submitted for the Degree of PhD
at the
University of St Andrews



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EXPERIMENTAL AND PETROLOGICAL INVESTIGATIONS OF SOME MAGMATIC PHENOMENA

By

P. J. WYLLIE

A thesis submitted to the University of St. Andrews in application for the degree of Doctor of Philosophy.

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Report on a Thesis submitted by Mr. P.J. Wyllie.

The thesis entitled "Experimental and petrological investigations of some magmatic phenomena" is devoted to a detailed investigation of a picrite sill of Tertiary age intruded into Torridonian strata on the island of Soay, south of Skye. It is divided into four parts (1) studies on the petrography of the picrite, (2) the thermal metamorphism of the enclosing Torridonian strata, (3) and (4) a considerati of the genetic problems of the picrite and the metamorphosed and partially fused Torridonian especially in the light of experimental data on silicate systems relate in composition thereto.

The first section gives in detail the mineralogy and petrography of one o the picrite sills of Harker's "later peridotite" group of intrusions and particular attention is devoted to the question of the habit of the olivine phase in its textural setting through the sill in the light of Bowen's reinterpretation of the conditions of intrusion of the Skye later peridotites. These descriptions are supported by one chemical analysis of an assemblage from the central part of the sill containing 61% modal olivine (62% normative olivine).

A fine grained offshoot from the sill into the country rock is described and it is noted that olivine phenocrysts in this are rare. The offshoot is tentatively regarded as a residuum squeezed from the picrite sill at a late stage of its crystallization (p.45). The chilled margins of the sill though reported to be picrite clearly contain much less olivine than the analysed rock and this is manifest from the detailed modal counts across the sill. The main problem posed by the textures of the sill is as the candidate states whether the olivine phenocrysts crystallized in situ or whether they were present as crystals when the magma was emplaced. The problem is left for discussion in a later section of the thesis. It is to be remarked at this stage however that it is regrettable that the candidate did not extend his chemical investigations more widely. Only one analysis of the sill is provided; chemical data on the chilled margin and on the fine grained offshoot are much to be desired in the discussion of these problems. Notwithstanding these lacunae, the candidate has provided a large mass of factual data, mineralogical and textural which are used to good effect in the discussions in the subsequent sections of the thesis.

Part 2 of the thesis deals with the metamorphism induced in the associated Torridonian sediments. This metamorphism culminated in partial fusion

of the sediments. The account of these phenomena, including the hybridism with the picrite is well set out and an analysis provided of a fused xenolith within the sill. In Part 3 an attempt is made in the light of experimental studies on a related silicate system to evaluate the liquidus of a picrite of the composition analysed. The discussion concerns the studies of Ricker on the Ca_2SiO_4-Mg_2SiO_4-Fe_2S plane in the quaternary system and the application of the results, with, it must be admitted, considerable extrapolation to the related picrite. It is concluded that th studies indicate that the liquidus of the picrite would be at considerably lower temperatures than suggested by earlier phase equilibrium work. A beginning with som experimental work by the candidate in the picrite itself in the presence of water vapour is reported but no liquidus determinations were recorded. The temperature deduced for the liquidus is roughly placed around 1500°C. with still lower values, if volatiles are allowed for. This temperature is still very high, at least 300°C. higher than that known for the liquidus of a calcalkali type of basalt.

The discussion of the fusion of the Torridonian assemblage in relation to the experimental data on the granite system (Ab-Or-SiO_2-H_2O) is well presented and probably provides a real picture of the processes involved. The final part of the thesis is devoted to the petrogenesis. Included here are discussions on the significance of the variations in the shape and size of olivine crystals, on the interpretation of porphyritic texture in relation to the olivine phase and the bearing of these phenomena on the question of <u>in situ</u> crystallization of olivine. The evidence considered unfavourable to the hypothesis of intrusion of a basaltic liquid containing a high proportion of olivine crystals is marshalled but not all of the argument can be regarded as cogent evidence.

The candidate has however brought forward good evidence from his own detailed studies that there are good grounds for extending the composition of true magmatic liquids beyond the limits given by Bowen. Such an extension had already been suggested by Drever in his study of West Greenland picrite sheets. Furthermore accumulating data on basalts themselves utilizing the same criteria adopted by Bowen have already indicated that Bowen's limits for normative olivine could be extended in certain cases to values at least up to 20 per cent. The candidate's own work provides such a confirmation but the critical data which could support the view that a picrite composition such as analysed in the centre of the Soay sill with 61% modal olivine was emplaced wholly in the liquid condition are not provided. In fact the evidence of the marginal transitions in this and other picritic minor intrusions is against such an interpretation.

Nevertheless, the candidate in his critical approach to the problem of picrites and peridotites has rightly laid emphasis on the need for further investigation of this difficult problem. His thesis suffers rather from lack of chemical data on critical assemblages met with on Soay and it is to be hoped that the experimental attack he began can be more closely prosecuted for it is clearly a fruitful line of approach.

I am of the opinion that the candidate has shown himself a competent investigator both on the petrographic and mineralogical aspects of his subject and has illuminated his study with an assessment of the results of experimental study on related silicate systems for his problem. He has produced as a result a thesis of originality and merit in the field of ultrabasic rocks and their contact phenomena. I have no hesitation in recommending him without further examination for the award of the Ph.D. degree.

Sgd. C.E. Tilley.

2/6/58.

PREFACE

Career

I matriculated in the University of St. Andrews in October, 1949, and followed a course in Pure Science until June 1952 when I graduated B.Sc. During the following two years I was a member of the British North Greenland Expedition. I returned to St. Andrews in October, 1954, and graduated with First Class Honours in Geology in July 1955. I was admitted as a research student to the University of St. Andrews in July, 1955 and pursued the prescribed programme of research in the Department of Geology, The University of St. Andrews, during the Academic Year 1955-1956, and in the Department of Geophysics and Geochemistry, The Pennsylvania State University, during the Academic Years 1956-1958.

Declaration

This is to certify that the thesis was composed by the candidate, contains a record of work completed by the candidate and has not been submitted in any previous application for a Higher Degree.

28/3/58

P. J. Wyllie

Certificate from Supervisor

I certify that Peter John Wyllie has fulfilled the conditions of Ordinance No. 16 (University of St. Andrews) and that he is qualified to submit this thesis in application for the Degree of Doctor of Philosophy.

Dr. H. I. Drever

ERRATUM

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CONTENTS

INTRODUCTION

A detailed investigation of a picrite sill of Tertiary age, intruded into Torridonian sediments on the west coast of Soay in the Hebrides, forms the principal subject of this thesis. The sill belongs to a group of non-alkaline picritic minor intrusions which Drever and Johnston (1958) studied in considerable detail, but essentially as a group, and it was chosen from the other intrusions of this group as the one most likely to justify a more extensive investigation. Thus the subject is not a random choice but a carefully selected topic which forms an integral part of the larger field of research on picritic rocks under the direction of Dr. H. I. Drever. The contribution of the thesis to this research is two-fold in character, involving (1) petrographic studies, and (2) correlation of the petrographical results with phase equilibrium studies of silicate systems.

Experience in phase equilibrium work was necessary in order to deal effectively with the second commitment, and this experience was gained while working as a Research Assistant to Professor O. F. Tuttle in the Department of Geophysics and Geochemistry at the Pennsylvania State University. During this time experimental studies were made on the effect of volatile materials on the melting relations of silicate minerals and rocks. It was not possible to confine the research to systems directly relevant to the field problem and the thesis is based, therefore, on only part of the completed research. However, close acquaintance with phase equilibrium studies has enabled the writer to select and discuss the experimental results which are most closely related to the petrographic studies.

The thesis is divided into four parts. Part I contains a detailed petrographic study of the picrite. Progressive thermal metamorphism of Torridonian sediment by the picrite culminated in extensive fusion, and the metamorphism and fusion are described in Part II. Part III is concerned with phase equilibrium studies relevant to the petrographic data, and in Part IV the significance of the petrological and experimental evidence is discussed and compared with evidence from other picritic minor intrusions of the group.

The quaternary system CaO-MgO-FeO-SiO_2 is particularly useful for depicting the chemical relationships among picritic rocks and it provides evidence that picritic liquids could exist at lower temperatures than suggested by earlier phase equilibrium work. The quaternary system albite-orthoclase-silica-water is equally useful for illustrating the relationships between the sediment and the fused products. This system has been discussed frequently by petrologists concerned with the genesis of granites and rhyolites and, by relating the metamorphosed sediment to the system, the observed products of selective fusion have been compared with normal granites, and with certain rocks of related compositions produced in similar environments by a process of metasomatism.

Variations in the shape and size of olivine crystals in the sill are described in detail, and it is concluded that the variations could have been produced by the crystallization of an essentially liquid magma. However, the range of temperatures involved in the other intrusions of the group indicates that if the sill was emplaced as a liquid, this was a rare occurrence. The possible influence of volatile materials is discussed in this connection. Deep-seated crystalline peridotite is considered the most likely source of picritic magmas in the neighbourhood of Skye, and the selective fusion of peridotite could make available

picritic magmas existing in a wide variety of physical states.

In recent decades the study of ultrabasic igneous rocks has received less attention than it warrants. The authoritative arguments of Bowen (1927, 1928) and the general acceptance by petrologists that crystal settling in basaltic magmas and crystallization differentiation are the dominant processes operating in petrogenesis have retarded critical re-examination of the many ultrabasic rocks exposed in the Hebrides. The uncritical acceptance of a single hypothesis to account for the origin of olivine-rich rocks in their many and varied occurrences is considered unjustifiable. It is hoped that the results of the research programme to which this thesis is a contribution will prompt (1) further detailed petrographic examination of other ultrabasic rocks, and (2) an extension of phase equilibrium studies in systems closely related to ultrabasic rock compositions. The continued necessity for such a combined attack on petrological problems was emphasized recently by Schairer in his introduction to the 1956 edition of Bowen's (1928) classic book: "The Evolution of the Igneous Rocks." He wrote: "The answers are in the rocks themselves, but a knowledge of the processes may provide the key that unlocks the secrets."

Acknowledgements

Following a reconnaissance by Dr. H. I. Drever in 1954, detailed field work on Soay was completed in 1955 by R. Johnston and the writer. The writer is indebted to Dr. H. I. Drever for suggesting the problem; to R. Johnston for stimulating companionship in the field, for photographing and printing the line drawings in the text, and for useful criticism of the manuscript; to Professors O. F. Tuttle and E. F. Osborn

for reading parts of the manuscript and to Professor J. C. Griffiths for advice concerning statistical methods; to the Shell Petroleum Company Limited for financing the field work in 1954; and to his wife for typing the thesis.

PART I

THE PETROLOGY OF A PICRITE SILL IN SOAY (HEBRIDES)

1. PREVIOUS WORK

The detailed mapping of Soay was completed during the survey of Soay and Skye by Clough and Harker (1904), and Harker (1904) discussed the igneous rocks of the island in his classic description of the Cuillin gabbroic complex. The sill which is the main subject of this thesis was grouped with the "later Peridotites" radiating from a mass of peridotite enveloped by gabbro near the centre of the complex. Harker (1904) used the name "peridotite" to include both peridotites and picrites. He considered that many peridotite intrusions were emplaced by the successive intrusions of basaltic and peridotitic liquids, the peridotite magma sweeping out the central portion of a partly consolidated dolerite intrusion (oral communication to Bowen 1928, p. 158).

Bowen (1927, 1928) later re-examined the complex and modified Harker's hypothesis, suggesting that the early intrusion of basaltic liquid was followed by a largely crystalline peridotite magma derived by the accumulation of olivine crystals in basaltic liquid. He has frequently cited the absence of high temperature metamorphism at the contacts of ultrabasic rocks (e.g. Bowen and Tuttle 1949) as evidence that they were not intruded as liquids, but in his examination of the Hebridean rocks he apparently overlooked some remarkable contact phenomena discovered by Clough. According to Harker (1904, p. 247):

> "Clough has observed three clear instances of the vitrification of grits in Soay, besides others in which the effects seem to be obscured by subsequent alteration. Some of these are in connection, not with basic, but with ultrabasic sills. The vitrification is only locally produced in the case of any given sill."

One of these sills is the subject of the present study.

Drever (1952) published some reasons for doubting the adequacy of the theory of olivine accumulation to explain the ultrabasic facies of

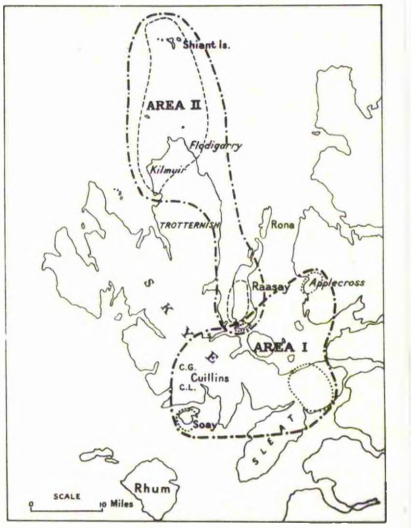

Figure 1. Areal distribution of picritic rocks in the Hebrides. Area I: non-alkaline picritic rocks. Area II: alkaline picritic rocks (after Drever and Johnston 1958). The investigated sill is on the island of Soay, in Area I.

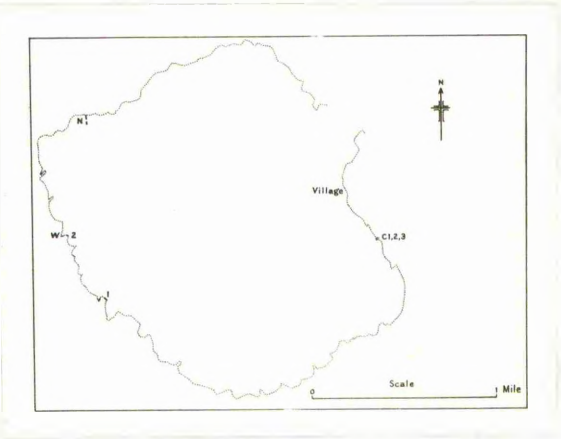

Figure 2. Sketch map of the main and west part of the Soay coast line, showing the positions of the picritic sills (after Drever and Johnston 1958). Sill 1 is on the west coast.

many sills and he advocated a more critical approach to the problem of the origin of olivine rich rocks. A re-investigation of the Hebridean group of ultrabasic minor intrusions by Drever and Johnston (1958) has demonstrated that their origin is neither so simple nor so well established as generally believed. Some of these intrusions have so many characteristics in common that they seem to constitute a natural group. There is evidence, however, of a range of intrusion temperatures within the group. No direct evidence was found of the participation of any normal basaltic magma from which olivine could have settled, and the variations were tentatively regarded as due to selective fusion of deep-seated ultrabasic material, which may possibly be the peridotite substratum identified elsewhere by seismic refraction studies. Whether or not the fusion temperatures were ever high enough to yield a picritic liquid was regarded as uncertain, since there is evidence that many of the olivines did not crystallize in situ; these could be xenocrysts of olivine drawn upwards by the liquid fraction from the region of fusion. Two distinct groups of picritic intrusions were recognized in the Hebrides, an alkaline and a non-alkaline group. The Skye group comprises the non-alkaline picrites whose distribution is shown in figure 1.

The present investigation is designed to test the hypotheses of earlier workers by means of a relatively intensive study of one carefully selected example of a picritic minor intrusion belonging to the group examined by Drever and Johnston (1958). Brown's (1956) detailed description of the layered ultrabasic intrusion of Rhum, although not strictly relevant to the present problem, constitutes a useful basis for the comparison of the mineralogy of the picrite with the mineralogy of ultrabasic rocks formed by the accumulation in basic magma of olivine and plagioclase feldspar.

2. FIELD RELATIONS

The non-alkaline picritic minor intrusions of the Hebrides occur within the area I of figure 1, and figure 2 shows the distribution of the sills on the island of Soay. The subject of the thesis, Sill 1, is located on the S.W. coast of the island, a quarter of a mile W.S.W. of the outlet of Loch Doir a' Chreamha.

The sediments on Soay are all of Torridonian age (Clough and Harker 1904) and in the neighbourhood of Sill 1 they belong to the Beinn Bhreac group. The predominant country rock is a feldspathic sandstone or grit, with varying degree of coarseness, which dips about 15° to the west. Sill 1, intersecting a thick dolerite dyke, was observed by Clough (Clough and Harker 1904) who recorded the presence of a fused xenolith of Torridonian grit at the place of intersection (plate 1B). The contact of this outcrop with sediment was not found (but see below). The sill varies slightly in width, averaging about 2 metres, and its field relations are illustrated in figure 3 and plate 1A.

The picrite is a dark green, coarse-grained rock, and olivine is readily distinguished by characteristic pits due to differential weathering (plates 1B and 2A). This mode of weathering makes it possible to trace, in the field, variations in the size and amount of olivine present. No change in the amount of olivine, or abrupt discontinuities in crystallization, were noted in Sill 1. At the south end of the exposure, however, there are several long, flat lenses of picrite weathering as distinct ridges which are aligned obliquely to the margins of the sill in sub-parallel fashion, with a slight apparent dip to the south-east (plate 2A). The margins of the sill are fissile and deeply

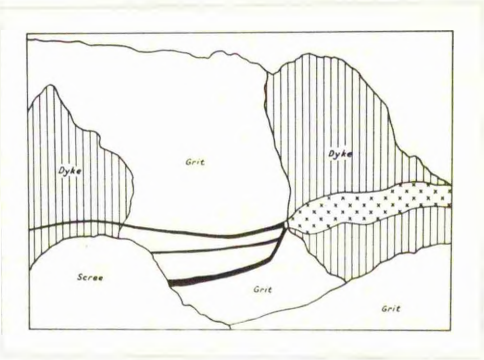

Figure 3. Field sketch of picrite Sill 1 (shown by crosses) intersecting a vertical dolerite dyke (shown by lines) seen in side view. From the sill extend fine grained offshoots (black). Compare plate 1A.

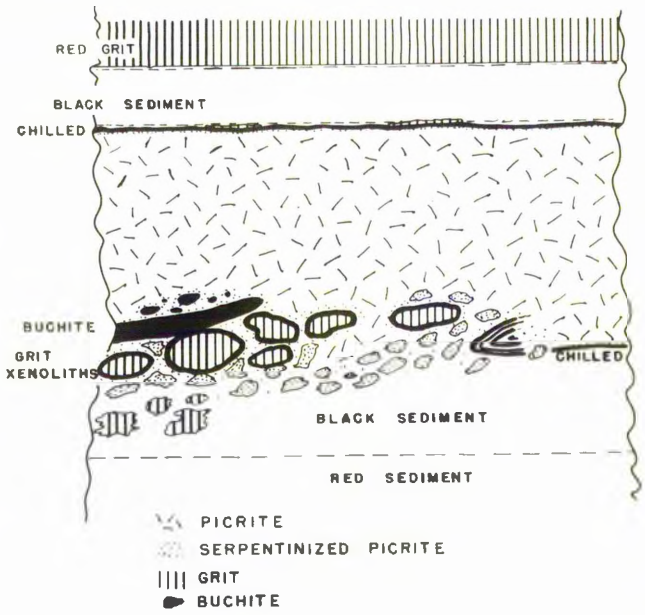

Figure 4. Diagrammatic sketch of the field relations of Sill 1A, just below high tide level on the wave cut platform below Sill 1. For the location of Sill 1 see figure 2. Compare plate 3A.

weathered for about 4 cms. from the contacts, but olivine can be detected in them. At its north end, the sill pinches out abruptly, and is replaced by narrow, fine-grained offshoots (figure 3 and plate 1A). The presence of a few olivine phenocrysts is shown by their characteristic weathering. The offshoots are initially about 30 cms. wide, often fissile, and their direction appears to be controlled by the bedding planes and joints within the sediment (plate 2B). The smallest offshoot extends for more than 30 metres, and is only 2 cms. wide where it pinches out. The transition between the picrite and the fine-grained offshoots could not be reached, but it appears to be fairly abrupt.

Another smaller outcrop of the sill, with upper and lower contacts against Torridonian sediment, was discovered just below high tide level on the wave cut platform about 30 metres from Sill 1. This outcrop, which will be called Sill 1A, contains several black, obsidian-like xenoliths, similar to the one mentioned above, as well as xenoliths exhibiting various degrees of fusion, and at the bottom contact of the sill the sediment is extensively fused. Sill 1 appears to occupy a slightly higher stratigraphic level than Sill 1A, but there is little doubt that the sills were once continuous. The fine-grained offshoots from Sill 1 transgress the sediments on a small scale (see figure 3) and the picrite could have behaved in the same way. Petrographically and mineralogically, the two outcrops are almost identical and the presence in Sill 1 of fused sediment emphasizes their similarity. Although the outcrops are regarded as two exposures of the same sill, they will be referred to specifically as Sill 1 and Sill 1A.

The width of Sill 1A is about 1 metre, but it is difficult to determine accurately because the basal contact is not everywhere sharply

defined, and the small outcrop is "stepped" by tidal erosion. The relationship of the sill to the country rock is illustrated in figure 4 and plate 3A. The upper margin exhibits a narrow chilled selvage containing a few small olivine phenocrysts, and the upper 50 cms. of picrite appears fresh and uniform in texture. Below this there extends a line of small, black glassy xenoliths and xenoliths of coarser grit. The grit xenoliths are surrounded by fine-grained rims of black vitrified sediment which is in contact with serpentinized picrite. The base of the sill has a narrow, well defined chilled margin at the east end of the exposure, but elsewhere the metamorphosed, vitrified sediment is mixed in intimate fashion with irregular blocks and fragments of serpentinized picrite and coarse grit (plate 8). Below the sill, fine-grained sediment has been partially vitrified and converted into a tough, black rock with the appearance of rapidly chilled basalt (plate 3A). Above the sill, the metamorphosed sediment forms a similar band, about 30 cms. wide, which is somewhat fissile towards its edges. The black vitrified sediment is locally separated from the sill by narrow seams of coarse red grit which appear in hand specimen to be unaltered. Similar coarse red grit lies above the metamorphosed sediment. The contact relations at the base of the sill are more irregular. The vitrified sediment grades downwards, through 30 to 50 cms., into a fine-grained, red feldspathic sandstone. Within the zone of metamorphosed sediment there are several irregular bodies of coarser grit, with gradational contacts against the fine-grained sediment (plate 8A). The metamorphosed sediment below the sill extends seawards further than the picrite, forming a prominent ledge. Within this ledge, a short distance from the picrite, the partially fused sediment is cut by a vertical, 10 cm. wide rheomorphic vein of black

glassy sediment containing small fragments of picrite. The vein has sharply defined contacts with the sediment and was clearly intruded into it (plate 3B).

Seven specimens of picrite were collected across Sill 1 and four were collected from Sill 1A. The numbers of the specimens and their positions relative to the margins of the sills are illustrated in figure 9. Twenty specimens were collected from the glassy xenoliths and partially vitrified sediment.

The exposures of Sill 1 and 1A are limited in extent and little direct information is available concerning their mode of intrusion, but evidence is available from other intrusions of the group (Drever and Johnston 1958). A characteristic feature of small picritic dykes in Coire Lagan, Skye, is their irregularity and variation in width. They may taper into veins, disappear from the surface and then reappear in a slightly offset position. The writer observed a similar displacement in the northernmost extension of the picrite sill N, on Soay (figure 2). (Harker, 1904, p. 369, also recorded displacements in basic minor intrusions of the Cuillins). The relations of three small picritic sills near the village on Soay (C1, C2, and C3 of figure 2) are irregular, and they indicate multiple intrusion. The suggested transgression from Sill 1 to Sill 1A therefore finds support in the characteristic irregularity of some other picritic intrusions of the group. The dolerite dyke appeared to act as an obstruction to the intrusion and this may account, in part, for the abrupt termination of Sill 1, and for the reduced width of Sill 1A. The irregular basal contact zone of Sill 1A, and the presence of fine-grained offshoots from Sill 1 suggest that considerable pressure was involved in the emplacement of the picrite.

3. MINERALOGY

The picrite is composed of olivine, calcic plagioclase feldspar, clinopyroxene and chrome spinel, together with minor alteration products. The compositions of the major constituents were estimated from optical measurements. Refractive indices were determined by the immersion method, and optic axial angles were measured on a four axis universal stage. The accuracy of refractive index measurements is ± 0.003, and the accuracy of universal stage measurements depends upon the method used and the properties of the mineral. All measurements were made in sodium light.

3.1. Olivine

The olivine is pale green in hand specimen and colourless in thin section. Alteration products are of localized importance only. The most striking feature of the crystals is their variation in shape and size. The crystals are idiomorphic, or nearly so, and the shapes represented in section range from equant to acicular, with elongation sometimes exceeding 10:1. Examination of the shapes of orientated sections reveals that many crystals are tabular parallel to (010). Many crystals, equant and elongated, large and small, have well developed skeletal forms. These are evenly distributed throughout the sills, and are not restricted to the rapidly chilled margins. Also common are parallel growths of large and small crystals and, in many examples, the forms could be described as either parallel growths or skeletal crystals (plate 6). Crystals range in size from large phenocrysts reaching 5 cms. in length to granules smaller than the uniformly crystallized feldspar and pyroxene, and there appears to be complete gradation in size from

the phenocrysts to groundmass crystals. The variations in shape and size of the olivine crystals will be discussed in more detail in a subsequent section.

The dendritic inclusions of ore occurring in the olivines of the "early peridotites" (Harker 1904) were not found in the olivines of Sill 1 and 1A, although inclusions of chrome spinel are common. Many of the olivine crystals contain rounded or oval inclusions, consisting of sub-parallel clinopyroxenes in a glassy or indeterminate base (plates 4 and 5). Oval shaped inclusions are elongated in the direction of elongation of the olivine. Other inclusions, indistinguishable in crystallinity from the groundmass, are probably in actual continuity with the groundmass (plate 5).

Of 110 olivine crystals examined on the universal stage, only 29 possessed any regular cleavage or parting, and only 6 of these had two cleavages (or partings). Seven crystals had a fine cleavage parallel to (010) and 2 had a fine cleavage parallel to (100). In 19 of the crystals, however, a coarse parting was developed parallel to (001) (Drever and Johnston 1957) and in 2 crystals partings existed parallel to (101) and (011). Irregular curving cracks are often present. Hawkes (1946) described olivine crystals with perfect cleavages parallel to (010) and (100), and occasionally with cleavages parallel to (001) and (110). In addition to the cleavages and partings, fine fractures parallel to the margins of the sill occur in some olivine crystals in Sill 1A, and these may extend through the groundmass pyroxene and feldspar. Similar fractures were not found in Sill 1. Drever and Johnston (1958) found fractures of this type in other intrusions of the group and regarded them as contractional features.

TABLE I. OPTICAL PROPERTIES AND ESTIMATED COMPOSITION OF OLIVINES

	SPECIMEN	β	COMPOSITION	(-)2V	COMPOSITION
Sill 1	48	1.665	$Fa_{6.5}$	93	Fa_7
	46	1.666	Fa_7		
Sill 1A	75	1.668	Fa_8	91.5	Fa_{10}
	74	1.662	Fa_5		
	73	1.665	$Fa_{6.5}$		

No twinning was found in the olivine but some crystals, distributed uniformly throughout the sills, exhibit translation lamellae sub-parallel to (100) (plate 7E). The difference in extinction angle between lamellae is small, reaching 10^{o} in some examples. Translation lamellae are shown by only a small proportion of the olivines but they occur in both large and small crystals. No common orientation of lamellae within the picrite could be distinguished. Rare crystals display undulose extinction (plate 7F). Similar features are common in the olivines of peridotites and dunites and they have been discussed in particular by Turner (1942), who considers them to be of undoubted deformational origin.

Extinction is sharp in most olivine crystals, but slight zoning was detected in some sections cut almost perpendicular to an optic axis (Tomkeieff 1939). The zoning is apparently restricted to narrow margins of the crystals, and it could not be confirmed on the universal stage.

The same value of 2V was found at the centre and outer edge of several crystals measured (see Appendix) so the range of zoning remains unknown, although it is probably small.

The composition of the olivine was estimated from the data collated by Poldervaart (1950), by measuring the refractive index β (on grains prised from thin sections) and 2V. The results are summarized in table 1. R. Johnston drew the writer's attention to reported discrepancies in 2V measurements of forsteritic olivine, and a systematic attempt was made to find the reason for the discrepancies. The methods used are described in the Appendix. The discrepancies appear to result from the refraction and displacement of light within the microscope slide and the stage mount. This causes an angular error which increases with increasing tilt of the universal stage. Unless a correction is made for the error, a single measurement of a mineral with 2V near 90^{o} is regarded as unreliable.

In the opinion of Tomkeieff (1939), the measurement of 2V is the best optical method for the determination of olivine, but Poldervaart (1950) and Wilkinson (1957) preferred refractive index measurements. From the measurements of 2V and β for the olivine of Sill 1, the estimated compositions agree closely, but in the case of Sill 1A the two methods give different compositions. Since only few refractive index measurements were made and many measurements of 2V give consistent results (see Appendix), more reliance must be placed on the latter. However, these indicate different compositions for the olivines of Sill 1 and Sill 1A which is difficult to explain if, as seems probable, they are different outcrops of the same sill.

The uncertainty in the accuracy of a single measurement of 2V makes

it difficult to determine whether there is a range of compositions between the large and small crystals, but the consistency of the 2V measurements implies that any compositional variation among the olivines of each sill must be very small.

The olivines of Sill 1 are more magnesian than the average composition of olivines from the picritic minor intrusions of the group, which is about Fa_{10}, and the olivines of both sills are more magnesian than those in the layered intrusion of Rhum, which have compositions near Fa_{14}, and more magnesian than olivines normally found in basalts (Brown 1956).

3.2. Plagioclase Feldspar

Calcic plagioclase feldspar appears as colourless laths, often arranged in sub-parallel fashion, which are separated by seams and wedges of clinopyroxene. Larger, irregular grains are also present. The laths are bounded by well developed crystal faces, but their terminations are irregular. Multiple twinning is seen in most lath sections, but not in the equant grains, and the crystals are therefore tabular parallel to (010). All crystals are strongly zoned, with outer zones richer in albite. Lath sections vary from 1 mm. to 2 mm. in length.

Attempts to measure the extinction angles of twin lamellae in the symmetrical zone were unsatisfactory and inconsistent on account of the zoning, and the composition of the feldspar was determined by refractive index measurements on cleavage fragments. A concentrated sample of feldspar fragments from each sill (specimens 48 and 74) was obtained with a Frantz isodynamic separator, and the greatest and least refractive indices of the cleavage fragments were measured. The ranges of

TABLE 2. REFRACTIVE INDICES OF FELDSPAR CLEAVAGE FRAGMENTS AND THE ESTIMATED RANGE OF ZONING

	SPECIMEN	RANGE OF REFRACTIVE INDICES	MINIMUM RANGE OF ZONING
Sill 1	48	1.579 - 1.562	An_{86} - An_{62}
Sill 1A	74	1.580 - 1.559	An_{88} - An_{59}

composition were estimated from the graphs of Tsuboi (1923: reproduced in Rogers and Kerr 1942, p. 244). The estimated range of zoning is, of course, smaller than the true range. Tsuboi's (1923) curves have not been modified (as far as the writer is aware) since the discovery that plagioclase feldspar exists in high and low structural states characterized by different optical properties (see Reynolds 1952 for summary). There is no doubt that, structurally, two series of feldspars exist (Smith and Yoder 1956) but the optical differences for the two series in the composition range An_{70} to An_{100} have not been established, although they are known to be small (see Muir 1955). In view of these uncertainties, the accuracy of the determined range of zoning cannot be estimated.

The smaller feldspars of the fine-grained offshoots from Sill 1 are also zoned but they were not separated and the range of zoning was not determined. The cores of the zoned crystals contain at least 64 molecular per cent of anorthite (determined by measurement of extinction angles in the symmetrical zone) and therefore have a composition similar to that of the outer zones of the plagioclase in the picrite.

In both sills, the plagioclase has essentially the same range of

zoning (table 2), and it is distinctly more calcic than the investigated feldspars in most of the picrite intrusions of the group (Drever and Johnston 1958). The range of zoning in two of the lower layers of the Rhum intrusion is comparable to that in Sills 1 and 1A, and Brown (1956) states that the unzoned feldspars of the intrusion, together with the cores of the zoned, closely approach a mean composition of An_{85}. According to Bowen (1928, p. 143) the most calcic composition of the total plagioclase of a uniformly fine-grained basaltic rock is about An_{67}. The feldspar in the picrite is uniformly fine-grained and considerably more calcic than this, but the composition of the plagioclase in the fine-grained offshoots is apparently similar to that found in basalts.

3.3. Clinopyroxene

Pale, non-pleochroic grey-brown clinopyroxene is present throughout the sills. Crystal faces are never developed, the pyroxene occurring as irregular grains and seams between idiomorphic plagioclase crystals. A few larger grains in Sill 1A reach diameters of 0.5 and rarely 1 mm. Prismatic cleavages are poorly developed and rarely seen in thin section. Two or three separate seams of pyroxene may be in optical continuity and, although zoning can rarely be detected in the smaller seams, the fact that larger crystals are often zoned suggests that the larger crystals to which the small seams belong are also zoned. No twinning was found.

The composition of the clinopyroxene was estimated by measuring the refractive index β (on grains prised from thin sections), and 2V. Direct double axis measurements of 2V were made on grains with B_{xa} nearly vertical, using the orthoscopic method, and the procedure described by

TABLE 3. OPTICAL PROPERTIES AND ESTIMATED COMPOSITION OF PYROXENES

	SPECIMEN	(+) 2V	β	COMPOSITION Ca	Mg	Fe
Sill 1	48	51.5	1.682	41	50	09
	47	52				
	46	50				
	45	51				
Sill 1A	74	51	1.679	40	53	07
	73	50.5	1.682	41	50	09
Specimen 74: $Z \wedge c = 42^{o}$						

Fairbairn and Podolsky (1950) was adopted. The range of eleven measurements of 2H in different crystals was 51^{o} to 53^{o}. Although zoning in some crystals can be detected by rotating the slide between crossed nicols, no difference in 2V between the cores and edges of such crystals could be established. The small size of most crystals prevented satisfactory measurements, but the range of zoning appears to be small. The location of an optic axis by its distinctive grey colour was much more definite than the location of an optic symmetry plane, and the writer agrees with Hess (1949) that measurement of 2V for pyroxenes by the single axis method is less accurate than one would suppose from the literature. However, the mean of several single axis measurements for olivines was found to agree closely with the mean of double axis methods (see Appendix) and the accuracy of single axis measurements therefore

appears to depend upon the properties of the mineral being examined.

The measured values of β and 2V are listed in table 3, together with the compositions inferred from the diagrams of Hess (1949). It is probable that minor amounts of Al_2O_3, Fe_2O_3, Na_2O etc. are also present in addition to the listed Ca, Mg and Fe (see Hess 1949). Only one determination of Z $\wedge$ c was made because of the poor development of cleavages and the difficulty of locating accurately the optic symmetry plane containing β. However, Z $\wedge$ c has little diagnostic value (Hess 1949, Muir 1951).

The estimated compositions of the pyroxene in each sill agree fairly well. Although the compositions of clinopyroxenes from other intrusions of the group are not yet known, their similarity is indicated by measurements of 2H, which range from 51° to 53°, reaching 57.5° in one sill (Drever and Johnston 1958).

The estimated compositions are a little lower in lime than an analyzed pyroxene from the layered intrusion of Rhum (Brown 1956) and the chrome diopsides from peridotite inclusions in basalts (Ross et alia 1954; plotted by Brown 1956, figure 5). They lie close to the beginning of the trend line for clinopyroxenes crystallizing from basaltic magma (Hess 1941). The pyroxenes are relatively richer in iron/magnesia than the coexisting olivines.

3.4. Chrome Spinel

Chrome spinel is distributed evenly throughout the picrite as regular octahedral sections and irregular grains. It is often enclosed by olivine. Most crystals are about 0.1 mm. in diameter but several reach sizes of 1 mm., or rarely 2 mm.; others are minute specks in the

groundmass. The mineral varies in colour from translucent reddish brown (near contacts and in the fine-grained offshoots) to opaque varieties indistinguishable from magnetite, and the variation in colour probably indicates a variation in the content of Cr_2O_3 (Fisher 1929). In thin parts of the sections and at the edges of otherwise opaque grains some colour is often visible. Many spinels contain central inclusions of indeterminate, birefringent material. They agree in all essential features with the chrome spinel described in other picritic intrusions of the group (Drever and Johnston 1958).

Harker (1904, p. 69) presented an analysis of picotite from a banded dunite on Skye and he believed that the brown translucent mineral in the other ultrabasic rocks is similar in composition, "and we may call it picotite". Ross *et alia* (1954) compared analyses of spinels from dunites and olivine rich nodules in basaltic rocks, and found that those from dunites were considerably richer in Cr_2O_3. The picotite from Skye (Harker 1904), in all major constituents, occupies the composition range of spinels from the olivine rich nodules.

It is possible that some of the opaque "spinel" is in fact magnetite, but no distinction could be made. Undoubted magnetite occurs as dusty particles where the olivine is serpentinized, and in the fine-grained offshoots, where it occurs as large amoeboid grains.

3.5. Alteration Products

The minerals composing the picrite are remarkably fresh except near the chilled margins and in contact with fused sediment, where the olivine is partially or wholly serpentinized. The serpentine varies from colourless to shades of green and yellow, and occasionally brown. Most

of the serpentine is antigorite showing fine lamellar structure between crossed nicols. Typical aggregate structures are radial or sub-parallel, and the presence within a single pseudomorph of several aggregates produces sometimes a herringbone structure and sometimes the appearance of a patchwork quilt. The refractive indices are greater than that of balsam, and less than those of olivine. All sections of lamellae are length slow indicating lamellar form parallel to (010). The mineral is biaxial with (-)2V between 40° and 60°. At the upper contact of Sill 1A and in the fine-grained offshoots all olivine crystals are completely pseudomorphed. Olivine crystals in contact with fused sediment may be completely or partially altered, the alteration proceeding from the edges of the crystals.

Near the upper contact of Sill 1, the picrite is deeply weathered and crumbly. This is due to widespread replacement of olivine and groundmass material by a deep brown product, possibly "iddingsite". Ming-Shan Sun (1957) gives evidence indicating that "iddingsite" does not have a definite chemical composition or optical properties, but is largely amorphous. It has been identified in the past by its colour, and by its association with olivine.

Replacement of olivine crystals by talc or carbonate is quite common in other minor intrusions of the group (Drever and Johnston 1958) and alteration to talc was reported by Bowen (1928) as a general tendency in the contact facies of the peridotite dykes in Skye. Neither talc nor carbonate was found replacing olivine, but a small vein near the base of Sill 1 contains carbonate. Other veins, trending parallel to the margins of the sill, contain short fibres of chrysotile, and olivine crystals traversed by such veins are partially serpentinized with the

release of considerable magnetite dust. It is possible that concentration of such veins may be responsible for the ridges in Sill 1 which weather differentially (plate 2A).

Small patches of chlorite replacing the feldspar and pyroxene are sometimes developed, particularly in areas where serpentinization of olivine crystals has proceeded farthest. Local chloritization of feldspar in the neighbourhood of serpentinized olivines is a characteristic feature of certain sills in Fife (Campbell et alia 1933).

4. PETROGRAPHY

4.1. Texture

The texture of the picrite is dominated by the high proportion of olivine (up to 60 per cent) occurring in a variety of shapes and sizes (figure 6). The plagioclase feldspar and pyroxene tend to be fairly constant in size within each specimen, and this size is much smaller than that of the olivine phenocrysts. The textural relationships of the feldspar and pyroxene remain much the same throughout each sill, but in Sill 1A the texture is distinctly coarser than in Sill 1 (plates 4 to 6). This may be related to a concentration of volatiles in Sill 1A near the basal contact zone of the sill (section 5)*. The feldspar attains its largest size in specimen 75, collected nearest to the zone of fusion (plate 4A). Chrome spinel, small in amount, is enclosed by all other minerals.

The texture of the picrite is porphyritic, the larger olivine phenocrysts contrasting sharply with the finer grained pyroxene and feldspar, but there are many olivine crystals intermediate in size. The frequent occurrence of skeletal forms and parallel growths in the olivine crystals of all sizes suggest rapid crystallization. Descriptions of these growth forms will be given in section 4.2.

The groundmass of Sill 1 exhibits sub-ophitic to sub-variolitic texture, using the latter term as defined by Drever and Johnston (1958). The pyroxene forms seams, wedges and granules (without crystal boundaries) between idiomorphic, tabular feldspar crystals which are often arranged in sub-parallel groups. True variolitic texture is only slightly removed from spherulitic structure and the relations between them were

* Part II

discussed by Harker (1909) and Tyrrell (1926). The texture suggests rapid growth from a number of centres of crystallization. In sill 1A, the texture is sub-ophitic (Krokstrom 1932), but coarse variolitic-type texture occurs also in the same specimens (plates 4C and D). From the texture it appears that feldspar began to crystallize before pyroxene, but Bowen (1928, p. 68 - 69) gives evidence that ophitic texture can result from the simultaneous crystallization of the two minerals. The calcic nature of the feldspar and calculation of the "f(norm)" (Barth 1936, discussed in section 6) suggest that the feldspar began to crystallize in the picrite before the pyroxene.

The feldspar crystals, generally 1 mm. to 2 mm. in length, are longest where they had room to grow between elongated olivine crystals. This sometimes gives the impression of "flow" of feldspar crystals around olivine phenocrysts in Sill 1 (plates 4A and 6F). Such an effect could have been produced by movement within the sill during the period of groundmass crystallization, but elsewhere in the same section the presence of sub-parallel groups of feldspars terminating abruptly against olivine phenocrysts shows that the stresses producing movement, if any, could have been neither vigorous nor of long duration. This textural feature was not observed in Sill 1A. The tendency for some tabular olivine crystals to be aligned parallel to the margin of Sill 1 (figure 6), particularly near the contact of the sill (plate 7B), could also have resulted from flow before the crystallization of the groundmass. The translation lamellae and undulose extinction occurring in some olivine crystals must be of deformational origin (Turner 1942), but if these olivine crystals are derivative (Hamilton 1957), the deformation could have preceded intrusion; otherwise it must have occurred at

a late stage of consolidation when the crystals formed a fairly rigid mesh. The fragile appearance of many tabular and skeletal crystals does not support vigorous movement.

Sub-parallel ridges are distinctive on the weathered surface of Sill 1 (plate 2A), but in thin section the mineralogy and texture of the rock appears identical with that of the main picrite. Walker (1940) described similar weathered ridges in the Palisades sill, but here they occur along joint planes and the development of biotite indicates the passage of hydrothermal solutions. No definite explanation of this weathering phenomenon can be offered at present, although it may result from concentrations of the small veins containing chrysotile.

The main problem posed by the texture is whether the olivine phenocrysts crystallized *in situ*, or whether they were present as crystals when the magma was emplaced. Discussion of this problem must await a more detailed description of the olivine crystals and the consideration of other evidence.

4.2. Variations in the Shapes of Olivine Crystals

The olivine crystals within the picrite are idiomorphic or sub-idiomorphic, but those enclosed by the fused sediment are corroded and rounded. The latter crystals will be described in Part II. The variety of shapes presented by sections of olivine crystals is illustrated in figure 6 and plates 4 to 7. The habit variation ranges from equant to extremely elongated for both large and small crystals, and the olivines present a variety of skeletal forms and parallel growths.

The variation of habit presented by 'a', 'b' and 'c' sections was determined. Using the universal stage, 110 suitably orientated sections

TABLE 4. THE HABIT VARIATION OF THE OLIVINE CRYSTALS

SECTIONS		EQUANT	ELONGATION <3:1	ELONGATION >3:1	IRREGULAR
	Elongation	-	'c'	'c'	-
'a'	Number	5	22	21	2
	Percentage	10	44	42	4
	Elongation	-	'a' 'c'	-	-
'b'	Number	32	6 2	-	-
	Percentage	82	13 5	-	-
	Elongation	-	'a'	'a'	-
'c'	Number	4	7	9	-
	Percentage	20	35	45	-

of large and medium sized crystals (but few small ones) were found. The crystals selected were classified into three habit groups: (1) equant, (2) prismatic, with elongation less than 3:1, and (3) accicular, with elongation greater than 3:1. Because the elongations of sections were estimated, and not measured, the classification is qualitative only, but the range of elongation (reaching up to 10:1) made such a classification possible. It was estimated that 27 per cent of the crystals examined were elongated more than 3:1.

The shapes and optical orientations of sections cut approximately perpendicular to each crystallographic axis are given in table 4, and the number and percentage of the crystals which occupy the three habit

groups is listed for each type of section. In the 'a' sections, cut parallel to (100), most crystals are elongated, with the elongation always parallel to 'c'. The 'b' sections, cut parallel to (010), are mostly equant and include no greatly elongated forms. More sections are elongated parallel to 'a' than parallel to 'c'. In the 'c' sections, cut parallel to (001), most crystals are elongated with the elongation always parallel to 'a'. The prevalence of elongated sections in crystals cut parallel to (100) and (001), and of equant sections in crystals cut parallel to (010) confirms that most of the crystals are tabular or lamellar parallel to (010). Some of the equant 'b' sections are indeed very large. The orientation of the elongated 'b' sections indicates that prismatic or columnar crystals may be elongated parallel to 'a' more often than parallel to 'c'. The existence of equant forms in 'a' and 'c', as well as in 'b' sections, suggests that some crystals may be equant. These conclusions agree in essence with those of Drever and Johnston (1957) in their investigation of habit variations of olivine crystals in other picritic intrusions.

The sectioned olivine crystals present not only a variety of habits, but also a variety of skeletal forms and parallel growths. That the development of these forms is a manifestation of similar factors is illustrated by plates 5 and 6, which show the transition from obvious skeletal crystals to forms which are normal parallel growths. A detailed account of the remarkable variety of growth forms assumed by olivine crystals, with specific reference to the Skye group of picritic minor intrusions, has been published by Drever and Johnston (1957), and the whole of their paper is relevant to this thesis. They conclude that the morphological and textural characteristics of the olivine crystals

described could be explained by growth along the two preferred directions 'a' and 'c', combined with incomplete inward growth. Rapid growth would tend to produce tabular and skeletal crystals, incomplete inward growth would enclose groundmass material, and if inward growth were completed normal parallel growths would develop. To describe in detail the skeletal forms and parallel growths occurring in Sill 1 and 1A would be unnecessary repetition, because many of the olivines described and illustrated by Drever and Johnston, particularly in elongated crystals, can be matched by examples from Sill 1 and 1A. Plates 4 to 6 illustrate the variety of forms present, and a brief description will suffice. The significance of these forms will be considered in Part IV, after the presentation of additional petrographic information.

Plates 5B to 5D illustrate relatively small, hollow olivine crystals with well developed crystal faces whose centres are filled with groundmass material. Direct connection of the included material with the groundmass is shown in plate 5C, and inferred in plates 5B and D. A similar feature occupies one half of a larger, elongated olivine in plate 5E. This plate illustrates also a greatly elongated olivine showing features suggesting skeletal crystallization (plate 5F). The skeletal crystals illustrated in plates 6B, C, D and E could justifiably be called parallel growths, and these may be regarded as types transitional to more normal parallel growths in which the parallel units are in close contact. The crystal in plate 6G consists of three units: a large centre one, with elongation 4:1, flanked by two smaller units. In plate 6F, the three parallel units are stouter and in plate 6H is illustrated the parallel growth of two units which are almost equant. Many large and small crystals are characterized by forked ends (plates 4B,

5G, H, 6A) which indicate almost complete inward growth of original skeletal crystals (compare plates 6B, C, and E). It should be emphasized that skeletal and parallel growths of olivine crystals are not restricted to any size group or habit group of the olivines in the two sills.

The tendency for elongated (tabular) crystals near to the margins of the sills to be aligned parallel to the margins is shown in plates 6C and 7B, but elsewhere in both sills, olivine crystals which are greatly elongated may be orientated in any direction within the sills (see figure 6).

4.3. Variations in the Size of Olivine Crystals

Most of the olivine crystals are smaller than, or of comparable size to the uniformly crystallized feldspar and pyroxene but others are very much larger. They could be described conventionally as phenocrysts, microphenocrysts and groundmass crystals, but there appears to be a complete gradation of sizes from the large phenocrysts to the small groundmass crystals. The coexistence of phenocrysts and groundmass crystals of olivine is generally accepted as evidence that the olivine crystals were precipitated in two "generations", with the inference, either stated or implied, that each "generation" crystallized in a distinct environment. The validity of such conclusions will be discussed in Part IV. The qualitative impression that there is a complete size gradation of the olivines of Sill 1 is confirmed by a quantitative statistical analysis of the sizes of the olivine crystals, and no distinct "generations" of olivine were recognized. If the olivine crystals were all about the same size a frequency distribution curve of dimensions

In the dimensional histograms the percentages of crystals with lengths and breadths greater than 1 mm. are less than 10 per cent and 1 per cent, respectively (figure 2). There are, of course, no crystals with zero length or breadth, and frequency distribution curves which could produce histograms of this type are sketched in figures 3C and D.. The curves are strongly skewed in a positive direction, with modes smaller than the first dimension class interval. The average size of the groundmass pyroxene and feldspar (estimated) is also smaller than the first dimension intervals in the histograms. Frequency distribution curves corresponding to the olivine histograms appear to be continuous from the small percentage of large phenocrysts, with a rapid increase in the percentage of smaller olivine crystals, which reaches a maximum within the size range of the groundmass crystals.

The area parameter gives a better indication of size than either length or breadth considered separately. Frequency distributions of the "areas" of crystals (with class interval 0.25 mm.^{2}) are similar to the others, with even stronger maxima in the smallest class intervals (figure 2). About 90 per cent of the crystals in each specimen are less than 0.25 mm.^{2} in area and these correspond to the groundmass crystallisation. There are a few crystals, particularly in specimen 49, with much greater areas. The corresponding frequency distribution curves (figure 3D) could be asymptotic towards the area axes, with no maxima to suggest that they belonged to another size distribution superimposed upon the main distribution. The phenocrysts appear to belong to the same distribution curve as the smaller crystals, and if were taken the gaps in the histograms (figure 2) would led.

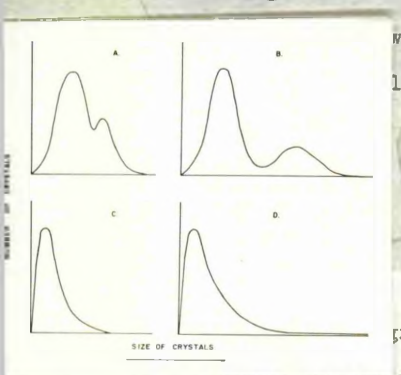

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Figure 3. Possible frequency distribution diagrams for the size [illegible] of olivine crystals.
A and B. Bimodal curves illustrating two groups of crystals overlapping different size ranges. These could be a "first" and "second" generation of olivines.
C and D. Frequency curves which could correspond with the observed distribution of the measured olivines.

grams for the elongation ratios are similar (figure 2). are 1 - 1.9, 2 - 2.9, etc. In this case, because there are many equant crystals with elongation ratio near 1, the corresponding frequency distribution curves would approach the J-type (Elderton, 1938). The only maxima, if any, on the corresponding frequency distribution curves must occupy the class interval 1 - 1.9, but the fabric of the picrite (figure 1 and plate II) is testimony that the phenocrysts (the only possible first generation of crystals) are not characterized by equant habit.

Space for Fig 3

The regular variations of ~~dimensions~~ lengths, breadths, "areas" and elongation ratios suggest that the growth of all olivine crystals was controlled by the same processes, and the rapid increase in the number of smaller crystals indicates a rapid change in the conditions accompanying their

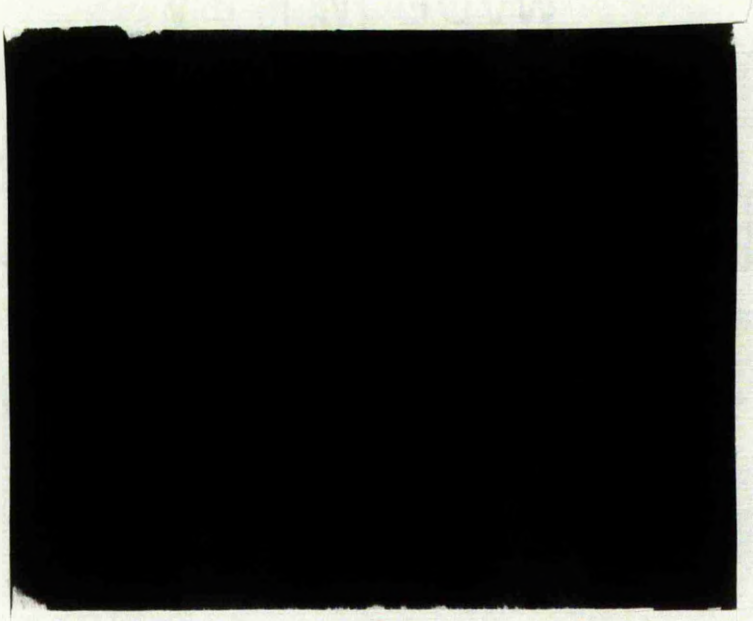

Figure 5. Possible frequency distribution diagrams for the size variation of olivine crystals.
A and B. Bimodal curves illustrating two groups of crystals occupying different size ranges. These could be a first and second generation of olivine crystals.
C and D. Frequency curves which could correspond to the observed distributions in the measured olivine crystals. See figures 7 and 8.

would approximate a normal distribution. Since the crystals would be cut in random sections the mode of the distribution would be at a value somewhat smaller than the true dimensions. If a rock contained two "generations" of olivine, occupying distinct size ranges, the frequency distribution curve would be bimodal as shown in figures 5A and 5B, with a maximum corresponding to each group of crystals. The maxima would be separated by an amount depending upon the size difference between the two groups of crystals.

The dimensions of olivine crystals were measured in three specimens, specimens 51 and 50 from near the upper margin of Sill 1, and specimen 49 from 30 cms. below the upper margin. Thin sections of the rocks were

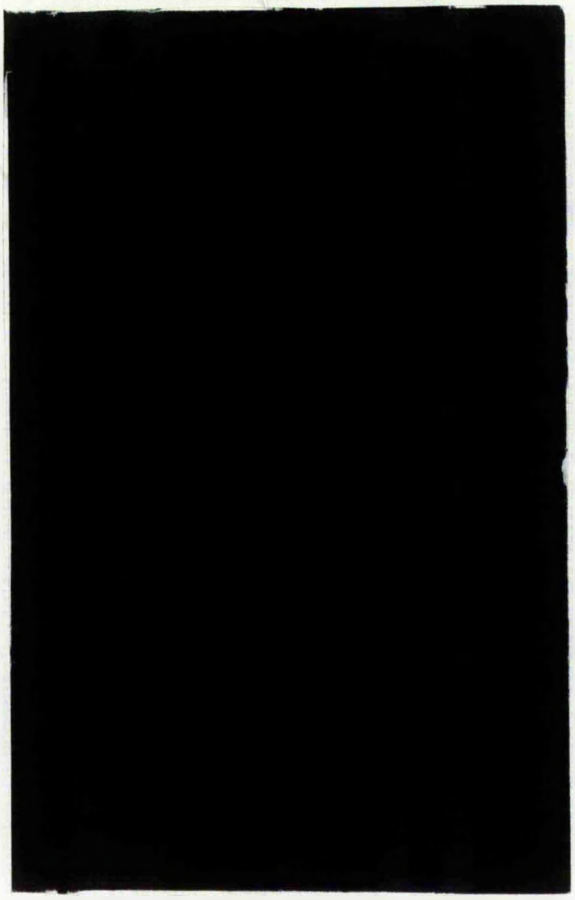

Figure 6. Scale drawing of the profiles of olivine crystals from three specimens in Sill 1, showing the distribution and the variation in shape and size of the olivine.

used as negatives in a photographic enlarger and an image of each section with a linear magnification of eight was recorded on hard printing paper. The olivine crystals stood out as black profiles from the feldspar and pyroxene. Tracings were made of the outlines of all olivine crystals except those extending across the edges of the print. Whenever there was some doubt as to the shape of the crystal in the print, the section was examined under the microscope. The greatest dimension (length) of each crystal was measured and the breadth was measured in a direction perpendicular to the length. Dimensions were measured on the tracings

Many of the olivines described and illustrated in this paper can be matched by examples from Sills 1 and 1A. It should be emphasized that skeletal and parallel growths of olivine crystals are not restricted to any size group or habit group of the olivines in these two sills. Elongated (tabular) crystals near margins of the sills tend to be aligned parallel to these margins, but elsewhere in both sills, elongated olivine crystals may be orientated in any direction (see figure 1).

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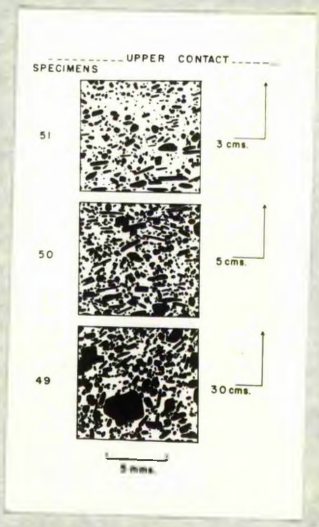


Figure 1 Scale drawing of the profiles of olivine crystals from three specimens in Sill 1, showing the distribution and the variation in shape and size of the olivine.

The Size of olivine

In size, most of the olivine crystals are smaller than, or equal to, the uniformly crystallised feldspar and pyroxene but others are very much larger. They could be described conventionally as phenocrysts, microphenocrysts and groundmass crystals, but there appears to be a complete gradation of sizes from the large phenocrysts to the small groundmass crystals. The co-existence of phenocrysts and groundmass crystals of olivine is generally accepted as evidence that the olivine crystals were precipitated in two "generations" with the inference, either stated or implied, that each "generation" crystallised under different P T conditions. ~~The validity of such conclusions will be discussed later.~~ A complete size gradation of the olivines in Sill 1 is confirmed by measurement of the sizes of olivine crystals, and no distinct "generations" could be recognised.

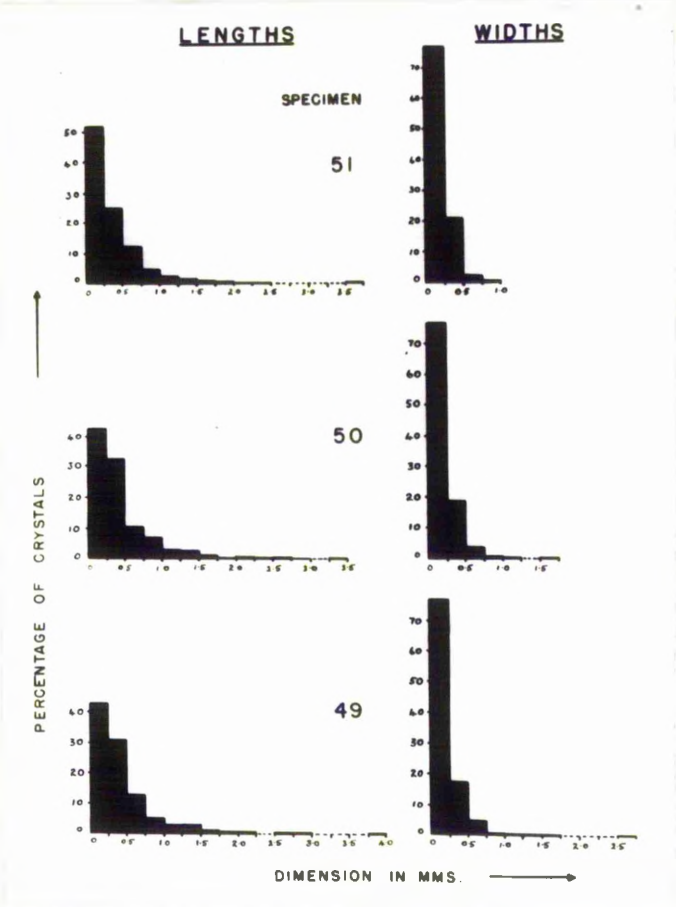


Figure 7. Histograms illustrating the variation in lengths and widths of olivine crystals in three specimens from Sill 1.

as multiples of 2 mm., corresponding to multiples of 0.25 mm. on the crystals, and they were recorded in the class intervals 0 - 0.25 mm., 0.25 - 0.5 mm., etc. The thin sections used were similarly orientated within the sill, perpendicular to the margins, and over 600 crystals were measured in each section. Although this may not ensure representative sampling of the rock, it standardizes the conditions for each sample and justifies the comparison of one with the others. The olivine crystals measured in portions of the prints are illustrated in figure 6.

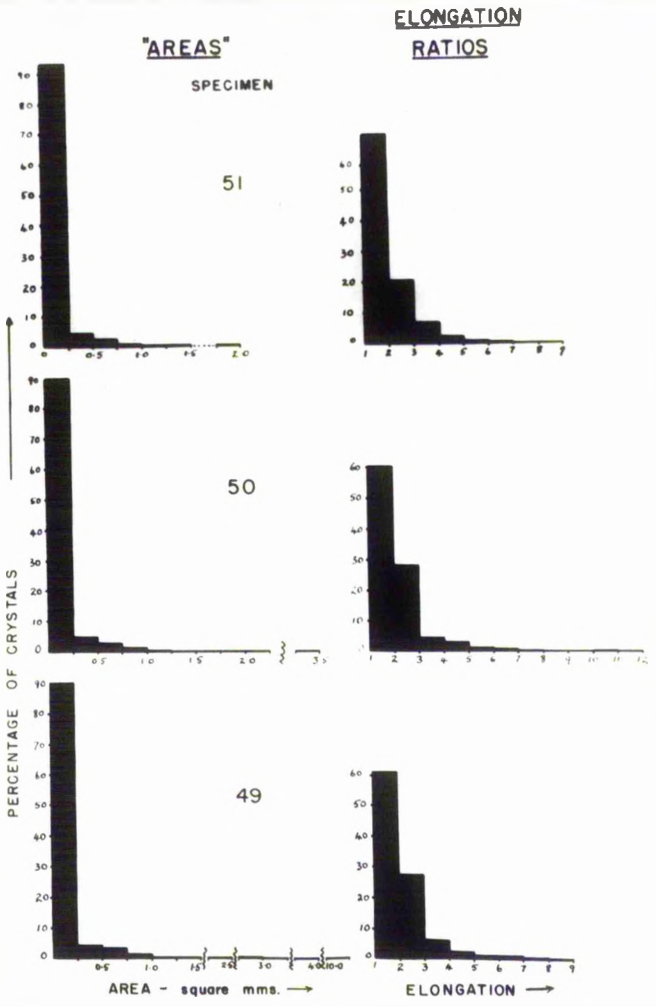


Figure 8. Histograms illustrating the variation of the "area" parameters and elongation ratios of olivine crystals in three specimens from Sill 1.

A measure of the area of each crystal was obtained by multiplying length by breadth. The dimensions used were not the absolute values, but were the mid-values of dimensional class intervals, e.g. the "area" of any crystal with length between 1.0 and 1.25 mm. and breadth between 0.25 and 0.5 mm. was recorded as 1.125 x 0.375 square mms. The values obtained are larger than the true areas because no crystals are rectangular in section. The elongation ratio of each crystal was obtained

by dividing length by breadth. Here, the upper limits of dimensional class intervals were used. These four values, length, breadth, area parameter and elongation ratio, permit a study of the variation of size and habit of the olivine crystals within each specimen and from one specimen to another.

Histograms have been constructed showing the distribution of these values (figures 7 and 8). The number of crystals in each class interval has been reduced to a percentage of the total number of crystals measured in each specimen to facilitate comparison among specimens. The total number of crystals, the arithmetic mean, the variance and the standard deviation for each distribution are listed in table 5. In each histogram, the highest percentage of crystals occupies the smallest class interval and the percentage of crystals in successive intervals decreases rapidly. None of the distributions is bimodal.

In the dimensional histograms the percentages of crystals with lengths and breadths greater than 1 mm. are less than 10 per cent and 1 per cent respectively (figure 7). There are, of course, no crystals with zero length or breadth, and frequency distribution curves which would produce histograms of this type are sketched in figures 5C and 5D. The curves are strongly skewed in a positive direction, with modes smaller than the first dimension class interval. The average size of the groundmass pyroxene and feldspar (estimated) is also smaller than the first dimension intervals in the histograms. The frequency distribution curves corresponding to the olivine histograms appear to be continuous from the small percentage of large phenocrysts, with a rapid increase in the percentage of smaller olivine crystals which reaches a maximum within the size range of the groundmass crystals.

The area parameter gives a better indication of size than either length or breadth considered separately. Frequency distributions of the "areas" of crystals (with class interval 0.25 square mms.) is similar to the others, with even stronger maxima in the first (smallest) class intervals (figure 8). About 90 per cent of the crystals in each specimen are less than 0.25 square mms. in area and must correspond to the groundmass crystallization. There are a few crystals, particularly in specimen 49, with much greater areas. The corresponding frequency distribution curves (figure 5D) would be asymptotic towards the area axes, with no maxima, suggesting that they belonged to another size distribution, superimposed upon the main distribution. The phenocrysts appear to belong to the same distribution curve as the smaller crystals, and if larger samples were taken the gaps in the histograms (figure 8) would probably be filled.

The histograms for the elongation ratios are again similar (figure 8). Class intervals are 1 - 1.9, 2 - 2.9 etc. In this case, because there are many equant crystals with elongation ratio near 1, the corresponding frequency distribution curves would approach the J-type (Elderton 1938). The only maxima, if any, on the corresponding frequency distribution curves must occupy the class interval 1 - 1.9, but the fabric of the picrite (figure 6 and plates 4 to 11) is testimony that the phenocrysts (the only possible first generation of crystals) are not characterized by equant habit.

The regular variations of dimensions, "areas" and elongation ratios suggests that the growth of all the olivine crystals was controlled by the same processes, and the rapid increase in the number of smaller crystals indicates a rapid change in the conditions accompanying their

TABLE 5. STATISTICS OF THE OLIVINE SIZE DISTRIBUTIONS

DISTRIBUTION	STATISTIC	SPECIMEN 51	50	49
	n	628	751	632
LENGTH IN MILLIMETRES	x	0.25	0.25	0.25
	$\bar{x}$	0.37	0.42	0.43
	s^2	0.14	0.19	0.18
	s	0.37	0.44	0.42
BREADTH IN MILLIMETRES	x	0.25	0.25	0.25
	$\bar{x}$	0.19	0.20	0.21
	s^2	0.02	0.02	0.04
	s	0.13	0.15	0.20
"AREA" IN SQUARE MILLIMETRES	x	0.25	0.25	0.25
	$\bar{x}$	0.163	0.178	0.206
	s^2	0.023	0.047	0.242
	s	0.152	0.216	0.493
ELONGATION RATIO	x	1	1	1
	$\bar{x}$	2.00	2.18	2.13
	s^2	0.89	1.52	1.11
	s	0.94	1.23	1.05

n is the total number of crystals measured in each specimen; x is the class interval in the stated units; $\bar{x}$ is the arithmetic mean; s^2 is the variance; s is the standard deviation.

growth. There is no evidence that the olivine crystals were precipitated in two "generations", which could be distinguished by a difference in habit, but in the "area" distribution for specimen 49, figure 8, 1.2 per cent of the olivine crystals, with areas greater than 2 square mms., are separated from the main part of the distribution. The interpretation given above was that these belong to the asymptotic part of a frequency curve of the type illustrated in figure 5D, but it is possible that they are not referable to the same distribution as the smaller crystals and it was calculated that these few phenocrysts constitute 26.9 per cent of the total "area" of measured olivine crystals in the specimen. The modal amount of olivine in this specimen is 54.0 per cent (table 6), and if all six phenocrysts are considered to be related to a size distribution distinct from that of the smaller crystals, they constitute only 14.5 per cent of the specimen by volume. This could represent a first "generation", and the remaining 39.5 per cent of olivine would then represent a second "generation".

Figure 6 shows the positions of the measured specimens relative to the upper margin of Sill 1. Specimens 51 and 50 are very close to each other, and close to the margin, whereas specimen 49 is within the main part of the sill. It can be seen from the "area" distributions, figure 8, that the number and size of the large olivine phenocrysts decreases as the upper margin of the sill is approached, and this is confirmed by the decrease in the mean area of the crystals in each specimen, table 5. The mean length of the crystals decreases only slightly from specimen 49 to specimen 50, but there is a greater decrease from specimen 50 to specimen 51. The mean breadth of the crystals decreases regularly from specimen 49 to specimen 51, but this implies a more rapid decrease in

the mean breadth close to the margin, because specimens 50 and 51 are so close to each other. The mean elongation ratio of specimen 51 is smaller than that of specimen 49, but that for specimen 50 is greater than either.

These relationships show that from the centre of Sill 1 towards the upper margin there is a slight decrease in the mean length, breadth, and "area" of the olivine crystals. Only very close to the contact do the dimensions begin to decrease more rapidly. The variation in mean elongation ratios implies that, close to the upper contact, the breadths of the olivine crystals initially decrease more rapidly than their lengths. Interpretation of the size variations of the olivine crystals will be discussed in Part IV.

4.4. Marginal Variations in the Picrite

Sills 1 and 1A are remarkably constant in mineralogy and texture except for the changes which occur in the narrow chilled margins. Contiguous specimens at the deeply weathered contacts of Sill 1 were not obtained, but enough specimens were collected to observe the textural changes near the contacts. A specimen collected about 7 cms. above the lower contact was in no way different from the specimens taken from the centre of the sill. In two specimens collected 5 and 3 cms. below the upper contact (specimens 50 and 51 respectively, plates 6C and 7B) the pyroxene and feldspar are distinctly finer grained than in the central part of the sill, decreasing in size as the contact is approached. The mean size of the olivine crystals decreases similarly but less rapidly (see statistics in table 5). Phenocrysts are still abundant but the proportion of very large phenocrysts decreases (figures 6, 7, and 8).

They are more manifestly tabular and skeletal, and some tabular crystals are parallel to the margin of the sill (figure 6 and plate 7B). In figure 8, the size distributions of olivine crystals in these two specimens was compared with that of a specimen collected 30 cms. below the contact, and the size and habit distributions of the olivine crystals in all three specimens differ in no essential respects. Approaching the contact, there is a decrease in the modal percentage of olivine which appears to be part of a regular variation across the sill (figure 9). Figure 6 shows that in specimen 51, nearest the contact of the sill, the olivine crystals are not evenly distributed. There is a narrow zone parallel to the contact in which olivine is deficient. Similar zones, attaining much greater sizes, were discovered by Drever and Johnston (1958) in other sills of the group. A decrease in the size of olivine crystals approaching the contact is apparent in this specimen (figure 6).

The base of Sill 1A has been chilled locally to a brown glassy selvage containing a few olivine crystals (visible in the field), but no specimen was collected from the selvage. Its width varies from 1 cm. to 2 cm.. The coarse texture of the picrite is not modified where it is in contact with the fused xenoliths (plate 8B) but in the basal contact zone, where blocks of serpentinized picrite and mobilized sediment are intimately mixed, the picrite has been contaminated (plates 8C and D) and olivine crystals have been isolated in a glassy matrix (plate 9D). Two specimens collected by Dr. H. I. Drever include the upper contact of the sill. Immediately in contact with the sediment, olivine crystals are set in a deep brown, almost opaque mesostasis. They range in size from minute birefringent specks to idiomorphic crystals reaching 2 mm. in diameter, and some crystals of intermediate size are

present (plates 7C and 7D). The olivine crystals, completely pseudomorphed by pale green antigorite, possess sharper crystal boundaries than those elsewhere in the picrite and there are fine examples of skeletal crystals, both equant and elongated. Apart from a few xenocrysts of quartz detached from the sediment, no crystals other than olivine and spinel are visible within 1 cm. from the contact, but an increasing number of small feldspar crystals may be distinguished from 1 cm. to 2 cm.. 2 cms. from the contact the groundmass is composed of a mesh of small feldspar crystals reaching 0.1 mm. in length with a few granules of clinopyroxene set in a brown, unresolvable mesostasis. No variation in size and habit of the olivine crystals was observed within the 2 cm. wide zone examined. The modal amount of olivine is 28 per cent. Passing further into the sill the grain size of the picrite, and the percentage of olivine, must increase rapidly, because in the specimen collected about 3 cms. from the upper contact of Sill 1 (specimen 51), the feldspars attain lengths of 0.25 mms., and the olivines are greatly increased in amount and size. Specimen 50, 5 cms. from the upper contact of Sill 1, is only slightly finer grained than the main part of the sill.

Bowen (1928, p. 150) grouped the margins of peridotite dykes in Skye and Soay into three main types, but the margins of Sill 1 and 1A, as well as the margins of some other minor intrusions of the group (Drever and Johnston 1958) do not correspond to any of these types.

It seems possible that most of the olivine present in the examined specimen of the chilled margin of Sill 1A (plates 7C and 7D) grew <u>in situ</u>. The material enclosed by the large and small skeletal crystals is identical with the brown isotropic groundmass. Some of the olivine phenocrysts may have been present before intrusion, and this possibility will be considered in Part IV. No large olivine phenocrysts trapped in the

chilled liquid were observed but many more thin sections would have to be examined before their complete absence could be confirmed. There is one small cluster of plagioclase crystals in the picrite collected 3 cms. from the upper contact of Sill 1 which is considerably larger than the other feldspars in the specimen (right hand side of plate 7B). In no other thin section of the picrite was such a cluster observed. The feldspars are about the same size as those in the picrite a little below this specimen.

That the chilled margin of Sill 1A is picritic in composition is beyond reasonable doubt. Chemical analyses of the fine-grained contact selvages of two other picrites of the group contain a much higher percentage of MgO than any normal basalt (Drever and Johnston 1958), suggesting that Sill 1A is not exceptional in this respect.

All of the olivine crystals in the chilled margins are serpentinized whether the contact is with the dyke or with the sediment. The alteration may have resulted from the diffusion of water from the country rock, but an alternative suggestion is that original magmatic water trapped within the chilled margins caused the alteration.

4.5. The Fine-grained Offshoots

The offshoots from Sill 1 are composed of a fine-grained assemblage of zoned plagioclase feldspar, granular pyroxene and olivine pseudomorphs (plate 7A). There are also a few grains of euhedral translucent spinel, and near the margins some amoeboid magnetite grains. The tendency for the (010) faces of the feldspar to grow at the expense of others, producing a tabular habit, is demonstrated by the forked ends of some lath sections. The laths vary in length from 0.25 mm. to 0.5 mm. Olivine,

pseudomorphed by pale green antigorite, constitutes 3.5 per cent (by volume) of the rock. The rare phenocrysts, attaining lengths of 2 mm., are generally elongated parallel to the margins and many of them are skeletal. A few of the smaller crystals contain inclusions of brown glassy material orientated parallel to the crystal faces. The reddish-brown spinel varies in size from 0.1 mm. to 0.5 mm. In colour it resembles the spinel found near the upper margin of Sill 1A. The grain size decreases rapidly towards the margins of the offshoots and locally, small tabular feldspar crystals are orientated parallel to the margins. This was not observed in the centre of the offshoots.

Since the cores of the feldspars have about the same composition as the margins of the zoned feldspars in the picrite, the offshoots may be regarded as a residuum squeezed from the picrite sill at a late stage of its crystallization. The small percentage of olivine and the absence of large phenocrysts suggest that expulsion of the liquid occurred at a late stage when the larger crystals in the picrite formed a fairly rigid mesh. The forces causing movement of the liquid from Sill 1 could also have produced, in the picrite, (1) the effects of strain observed in some olivine crystals, and (2) the local moulding of feldspar laths around olivine phenocrysts. That the expulsion of liquid was rapid is suggested by the orientation of feldspar tablets near the margins of the offshoots. Movement must have ceased by the time the central parts consolidated. It is desirable to examine further the transition between the picrite and the offshoots, which appears to be continuous (plate 1A, figure 3).

5. MICROMETRIC DATA

The volumetric proportions of the minerals comprising the sill were recorded with a Swift point counter (Chayes 1949) and the results are recorded in table 6. Points were made at intervals of 0.1 mm. in traverses 0.3 mm. apart. Only in two specimens were the number of points less than 3,000. In figure 9, the volumetric percentages are plotted against the positions of the specimens in the sills in order to show the variation of the minerals across the sills. According to Chayes and Fairbairn (1951) the accuracy of point counter analysis, with reasonable care and practice, can easily equal that of analytical methods ordinarily regarded as inherently more precise. The highest degree of accuracy may be obtained for even grained rocks with an optimum degree of crystallinity. Sources of error in the measurements include: (1) incorrect identification of minerals, (2) the operator's bias, and (3) error in sampling.

Identification of minerals in the picrite presents no problem and the error in this respect must be negligible. The operator's bias will be similar in all specimens examined and can be neglected when the variation across the sill is being considered. The sampling error, however, cannot be neglected. Larsen and Miller (1935) believed that failure of a section to give a proper sample of the rock introduces an error of two to ten per cent in modal determinations on different sections of the same rock. The large variation in the size of olivine phenocrysts increases the difficulty of proper sampling. In order to find the possible magnitude of the sampling error two and three sections respectively were examined from specimens 48 and 45. Sections from specimen 48 were cut in directions parallel and perpendicular to the

TABLE 6. THE MODAL VARIATION OF MINERALS WITHIN THE SILLS

SPEC.	TRAV.	OLIV.	PYR.	FEL.	SPIN.	REST	OL PY	PY/FEL
			SILL 1. WIDTH: 2 METRES					
51	26.7	38.9	26.1	19.8	3.8	11.4	65.0	1.32
50	34.1	47.6	24.9	23.5	3.2	0.8	72.5	1.06
49	43.4	54.0	19.1	23.0	3.5	0.3	73.1	0.83
48	67.9	59.9	13.8	22.0	2.5	1.9	73.7	0.63
47	33.5	59.7	11.3	24.7	2.2	2.1	71.0	0.46
46	33.9	57.8	15.4	23.0	2.9	0.9	73.2	0.67
45	130.0	53.9	19.6	23.6	2.2	0.8	73.5	0.83
48.1	31.9	60.9	12.6	22.8	1.9	1.8	73.5	0.55
48.x	36.0	58.8	15.0	21.2	3.0	1.9	73.8	0.71
45.1	43.2	56.4	17.8	23.0	1.6	1.2	74.2	0.77
45.p	44.4	53.3	19.4	24.6	1.9	0.9	72.7	0.79
45.x	42.4	52.0	21.6	23.1	3.1	0.2	73.6	0.94
			SILL 1A. WIDTH: 1 METRE					
136	24.0	28.0	-	-	-	72.0	-	-
73	44.1	57.0	15.7	23.3	2.2	1.8	72.7	0.67
74	59.2	61.0	13.9	21.6	2.5	1.0	74.9	0.64
75	36.3	53.3	19.7	21.8	3.4	1.8	73.0	0.90

SPEC. - specimen. TRAV. - length of traverse in centimetres. OLIV. - olivine. PYR. - pyroxene. FEL. - feldspar. SPIN. - spinel. OL PY. - olivine plus pyroxene. PY/FEL. - pyroxene/feldspar ratio.

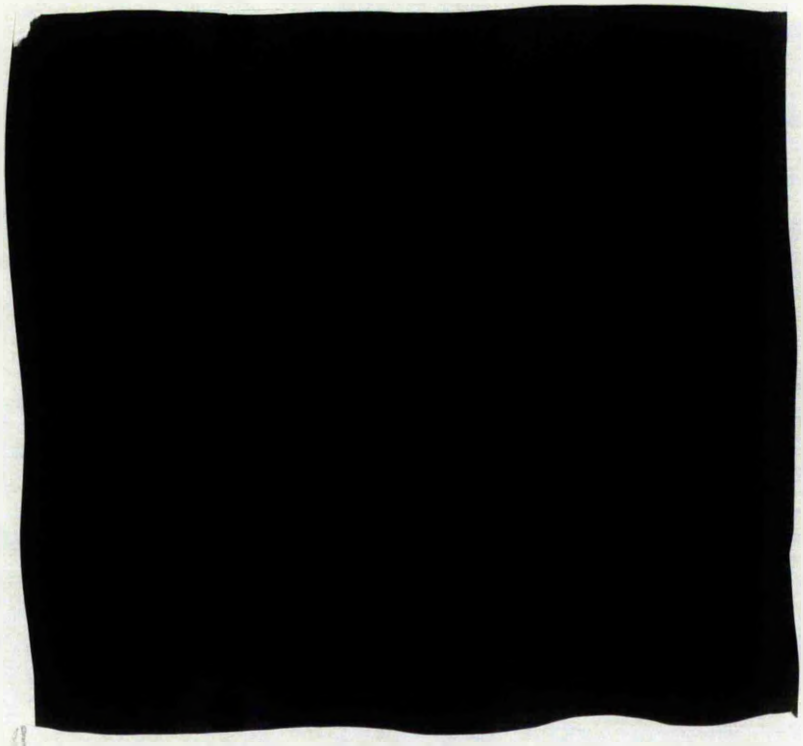


Figure 9. Diagram illustrating the positions of collected specimens of picrite relative to the margins of Sill 1 and 1A. The points represent determined modal proportions of the minerals in each specimen and the lines through the points show the modal variation of each mineral across the sills. For specimen 51, the crosses represent the modal percentages of minerals after adjustment has been made for the serpentine occurring in this specimen.

margin of the sill and the sections from specimen 45 were cut in three directions at right angles to each other, one section being parallel to the margin of the sill. The difference between extreme values obtained for olivine amounts to 2.1 per cent in specimen 48 and 4.4 per cent in specimen 45, with smaller differences between determinations for the other minerals (table 6). The average of separate determinations has been taken as the best value for these specimens. The differences obtained in the measurements of sections cut in different directions

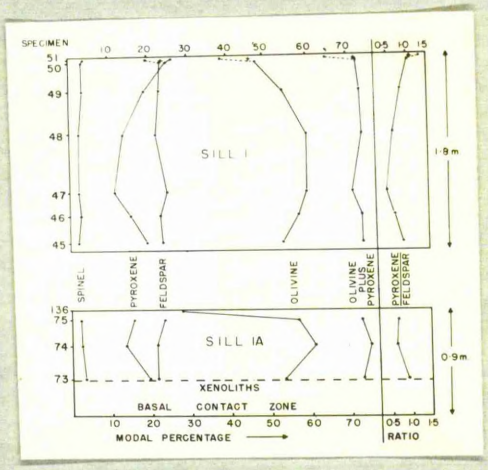


Figure 4. Modal variation diagram from top to bottom of Sills 1 and 1A. In the case of specimen 51, the crosses represent the modal percentages of minerals after an adjustment has been made for serpentine.

demonstrate an appreciable sampling error, but the range of error indicated by the measurements is much less than the total variation of the minerals illustrated in figure 9, and the error is therefore unlikely to affect either the variation trends, or the validity of the conclusions drawn from the trends.

In Sill 1 the specimens were collected from a plane vertical exposure, and their distances from top and bottom of the sill were readily measured. In Sill 1A, the basal contact zone is irregular and the outcrop has been "stepped" by tidal erosion, so the positions of the specimens relative to the margins were less readily measured. Specimen 136 from Sill 1A includes the upper contact with the sediment. The olivine has been completely serpentinized but is recorded as olivine. The cryptocrystalline or glassy groundmass permitted no further determinations. A more complete representation of the mineral variation is available for Sill 1 than for Sill 1A and discussion of the variation will be confined to Sill 1. The determinations for Sill 1A are similar in their general trends.

Spinel is constantly present ranging from 2.2 to 3.8 per cent. The feldspar proportion remains fairly constant between 22.0 and 24.7 per cent, with the exception of specimen 51. This specimen will be considered separately below. Clinopyroxene is highest in amount towards the margins of the sill with a pronounced decrease in the central portions, the range being from 11.3 to 24.9 per cent. The distribution is asymmetrical with respect to the margins, with the minimum percentage of pyroxene occurring at a level below the median line of the sill. Olivine shows a definite increase in proportion in the central parts of the sill, the variation being from 47.6 to 59.9 per cent. The maximum

percentage occurs somewhat below the median line. At the upper contact of Sill 1A (specimen 136) olivine is reduced to 28.0 per cent.

The plotted points for the percentage of olivine plus pyroxene are remarkably constant, and the ratio of pyroxene/feldspar shows a decrease from the margins of the sill to a minimum below the median line. Recalculating the volumetric percentages in terms of weight percentages simply increases the percentages of olivine, pyroxene and spinel and decreases that of feldspar. The variation trends are not appreciably affected.

The points in figure 9 indicate regular trends in the mineral variation across Sill 1, with the exception of points for specimen 51. Whereas the other specimens contain only 1 or 2 per cent of "Rest", i.e. serpentine etc., specimen 51 contains 11.4 per cent. For the purpose of comparison the alteration products should be partitioned between olivine and feldspar. Attempts to do this empirically were unsuccessful owing to the density of the "iddingsite" which spreads from many olivine crystals, obscuring detail in the groundmass. However, if the correct amount of olivine before alteration were 45.9 per cent the total olivine plus pyroxene would be 72.0 per cent, corresponding to the value obtained for the other specimens. If 7.0 per cent of the alteration products is then assigned to olivine, the remaining 4.2 per cent may be added to feldspar bringing the feldspar percentage up to 23.8. The adjusted values conform closely to the variation across the rest of the sill.

6. CHEMICAL ANALYSIS

Specimen 74 from Sill 1A was analyzed and its analysis is compared with those of other peridotites and picrites in table 7. The norm, and the calculated compositions of the normative minerals of the specimen are compared with the mode and estimated mineral compositions in table 8. The norm corresponds closely to the mode, as would be expected in a rock of such simple mineralogical composition. The normative pyroxene is notably lower than the modal percentage and the normative plagioclase is more calcic than the estimated feldspar composition. These differences are related, because some of the Al_2O_3 calculated as normative anorthite is probably present in the modal pyroxene (Bowen 1928, Hess 1949).

The chemical analysis is more meaningful if it is compared with analyses of other picritic rocks to which it is related, and chemical variation diagrams will be discussed in Part IV. Some of the analyses which will be used in the variation diagrams are listed in table 7 for immediate comparison. The picrite is very similar in composition to the peridotite from Skye, and it is poorer in magnesia and iron than the peridotite from the Rhum intrusion. The other analyses from Skye illustrate the wide range of MgO content which occurs in picritic rocks, and the picrite basalt from Greenland appears to occupy a position between the picritic rocks 3 and 4 from Skye.

The "f(norm)" was obtained by recalculating the normative albite, anorthite, diopside and hypersthene to 100 per cent, and adding together the recalculated albite, diopside and hypersthene. The total is 36. According to Barth (1936), in basaltic rocks with "f(norm)" less than

TABLE 7. CHEMICAL ANALYSIS OF PICRITE FROM SILL 1A COMPARED WITH ANALYSES OF OTHER PICRITIC AND ULTRABASIC ROCKS

	1	2	3	4	5	6
SiO_2	41.86	40.90	44.61	47.28	41.06	45.04
Al_2O_3	8.82	7.56	10.86	14.63	4.82	12.77
Fe_2O_3	1.46	3.01	2.31	1.83	2.07	2.83
FeO	8.14	7.31	7.46	9.87	9.46	9.02
MgO	31.56	29.63	21.06	10.42	36.15	16.09
CaO	5.38	5.40	9.01	10.38	4.27	9.14
Na_2O	0.56	0.98	1.15	1.73	0.65	1.78
K_2O	0.04	0.37	0.19	0.33	0.02	0.26
H_2O	1.62	2.98	1.17	1.66	0.97	1.35
H_2O -	0.28	0.13	0.05	0.28	0.06	0.65
TiO_2	0.29	1.70	2.25	1.22	0.15	0.89
MnO	0.14	0.34	0.16	0.11	0.17	0.18
P_2O_5	trace	0.10	0.10	0.05	-	0.18
Cr_2O_3	-	0.11	trace	-	0.51	-
CO_2	-	-	-	0.44	-	-
	100.15	100.52	100.38	100.23	100.36	100.18

1. Picrite from Sill 1A, specimen 74. Analyst: W. H. Herdsman (New Series).
2. Peridotite dyke, Coir' a' Greadaidh, Isle of Skye. Analyst: M. G. Keyes (Bowen 1928, p. 154).
3. Picrite dolerite dyke, Coir Labain, Isle of Skye. Analyst: M. G. Keyes (Bowen 1928, p. 154).
4. Variolitic olivine basalt at upper contact of intrusive sheet, Camas Daraich, Point of Sleat, Skye. Analyst: W. H. Herdsman (New Series) (Drever and Johnston 1957).
5. Peridotite from the layered intrusion of Rhum. Analyst: E. A. Vincent (Brown 1956).
6. Picrite basalt from picritic sheet (Sheet 4), east coast of Ubekendt Ejland, West Greenland. Analyst: W. H. Herdsman (New Series) (Drever and Johnston 1957).

TABLE 8. COMPARISON OF THE NORM AND MODE OF THE ANALYZED PICRITE

NORM		MODE	
ab	4.7	Plagioclase	21.6
an	21.4		
di	2.2		4.2
	1.7		
	0.3	Clinopyroxene	13.9
hy	2.8		3.3
	0.5		
ol	52.1	Olivine	61.0
	9.8		
mt	2.1	Chrome spinel	2.5
il	0.6	Serpentine	1.0
Plag	$Ab_{10.5}An_{89.5}$	Plag	$Ab_{12}An_{88}$ to $Ab_{41}An_{59}$
Diop	$Wo_{50}En_{44.7}Fs_{5.3}$	Clinopyroxene	$Wo_{40}En_{53}Fs_{7}$
Hyp	$En_{87.5}Fs_{12.5}$		
Oliv	$Fo_{88.6}Fa_{11.4}$	Olivine	$Fo_{90}Fa_{10}$

123 feldspar began to crystallize before pyroxene, and in those with "f(norm)" greater than 123 pyroxene began to crystallize before feldspar. It is not known whether the same relation holds for rocks as rich in olivine as the picrite, but the extremely low value of the "f(norm)" may be regarded as evidence that the feldspar began to crystallize before the pyroxene.

PLATES 1 TO 7

Plate 1.

A. Side view of a dolerite dyke intersected by a picrite sill, Sill 1. The sill continues at the bottom left of the photograph as narrow, fine-grained offshoots. Compare figure 3. The man on the right shows the scale.

B. The southeastern exposure of Sill 1 (the right side of plate 1A). The pitted surface of the picrite is characteristic and results from the weathering of olivines. The arrow indicates the position of a black, obsidian-like xenolith of fused sediment.

Plate 2.

A. The southeastern exposure of Sill 1. The picrite is less resistant to weathering than the dolerite, and the ledge on which the hammer rests is formed of dolerite. The cause of the subparallel ridges on the weathered surface of the sill was not established. The hammer shaft is marked in inches.

B. Fine-grained offshoot extending northwards from Sill 1. The wall of the dyke is exposed in the left of the photograph but slabs of grit cover the dyke to the right. The fine-grained offshoot is deflected along a joint plane within the sediment.

Plate 3.

A. The basal contact zone of Sill 1A. The sill occupies the upper half of the photograph and partially vitrified sediment occupies the lower half. Above blocky weathering vitrified sediment is a zone in which serpentinized picrite and fused sediment are intimately mixed. Coarse-grained grit xenoliths extend in a band parallel to the basal contact zone at a level just below the top of the hammer. Compare figure 4.

B. Rheomorphic vein of fused sediment in the country rock. The vein extends approximately parallel to, and to the right of the hammer. The view is looking vertically downwards on to the exposure.

Plate 4.

Textures in the picrite. Scale: x18.

A. Specimen 49, Sill 1. The texture of the pyroxene and feldspar is characteristic of the sill.

B. Specimen 75, Sill 1A. The texture of the pyroxene and feldspar is characteristic of the sill, and notably coarser than in Sill 1. The feldspar is somewhat finer grained in other specimens from Sill 1A - see plates 4C and 5H.

C. Specimen 74, Sill 1A. Elongated olivine crystal with a long, central inclusion containing accicular clinopyroxene. Plagioclase occurs in a parallel group separated by narrow seams of pyroxene.

D. The same as plate 4C with nicols crossed.

Plate 5.

Skeletal olivine crystals in the picrite. Scale: x18.

A. Specimen 73, Sill 1A. Olivine crystal containing a small inclusion of pyroxene and feldspar with radial structure.

B. Specimen 50, Sill 1. Olivine crystal with hollow centre enclosing groundmass.

C. Specimen 45, Sill 1. Skeletal olivine crystal partially enclosing groundmass material.

D. Specimen 45, Sill 1. Skeletal olivine crystal (extinction position) enclosing groundmass material. Just below this is an olivine with a small round inclusion.

E. Specimen 49, Sill 1. Skeletal olivine crystal in the extinction position enclosing groundmass material.

F. The same as plate 5E, with an elongated, skeletal olivine rotated into the extinction position. The plagioclase has a tendency to wrap around the olivine.

G. Specimen 49, Sill 1. Skeletal olivine crystal.

H. Specimen 73, Sill 1A. Elongated olivine crystal with forked end. This is similar to the smaller crystal in plate 5G. Compare also plate 6A.

Plate 6.

Skeletal and parallel growth in olivine crystals. Scale: x18.

A. Specimen 49, Sill 1.
B. Specimen 73, Sill 1A.
C. Specimen 50, Sill 1.
D. Specimen 74, Sill 1A.
E. Specimen 50, Sill 1.
F. Specimen 49, Sill 1.
G. Specimen 73, Sill 1A.
H. Specimen 47, Sill 1.

Plate 7.

A. Fine-grained offshoot from Sill 1. Olivine occurs as pseudomorphs. One of the olivine phenocrysts has a hollow centre, compare plate 5A. Scale: x18.

B. Specimen 51, Sill 1. This specimen was collected about 3 cms. from the upper contact of the sill. The olivine crystals are marginally altered to "iddingsite" which also spreads through the fine-grained groundmass. Note the tendency for elongated olivine crystals to be aligned parallel to the contacts (compare figure 6). At the right side of the photograph there is a group of parallel plagioclase crystals, much larger than those occurring in the groundmass. Scale: x18.

C and D. Specimen 136, Sill 1A. The upper contact of the sill with Torridonian sediment. The prints are negatives of two different sections from the specimen. The brown glassy mesostasis of the picrite appears white in the photograph, and the olivine pseudomorphs are grey. The small grey specks in the white background represent olivine. The transparent minerals in the sediment appear as black grains. In several places there are holes in the slide (black) marking the former positions of olivine pseudomorphs. Several skeletal olivines can be distinguished. Large olivines (2 mms.) are present at the contact. Scale: x4.

E. Specimen 49, Sill 1. Translation lamellae in olivine. Scale: x18.

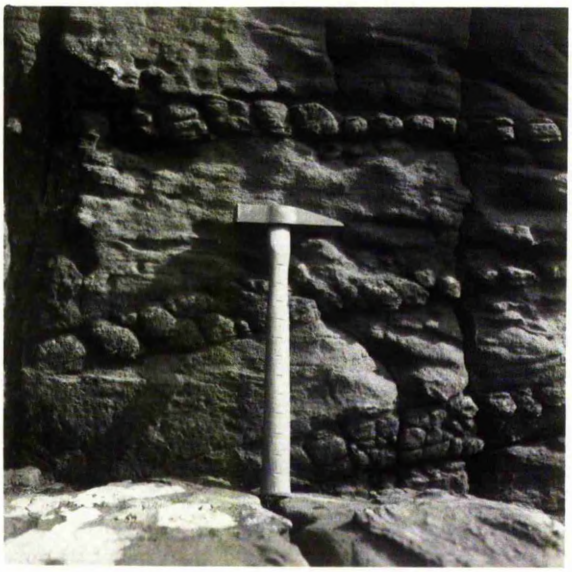
F. Specimen 49, Sill 1. Undulose extinction in olivine. Scale: x18.

PLATE 1.

A.

B.

PLATE 2.

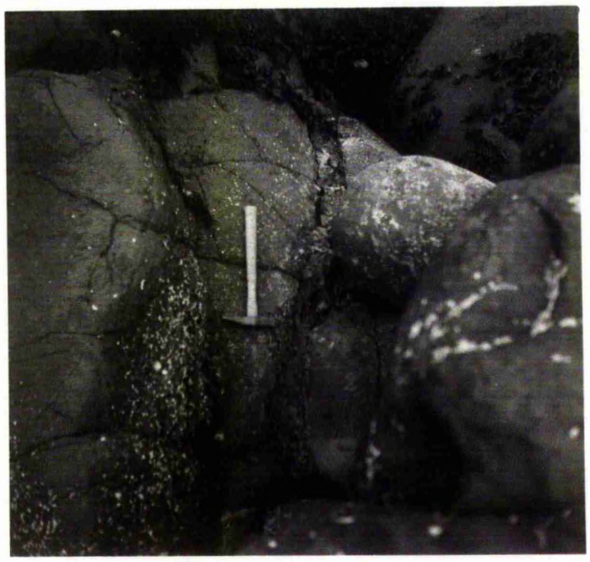


A.

B.

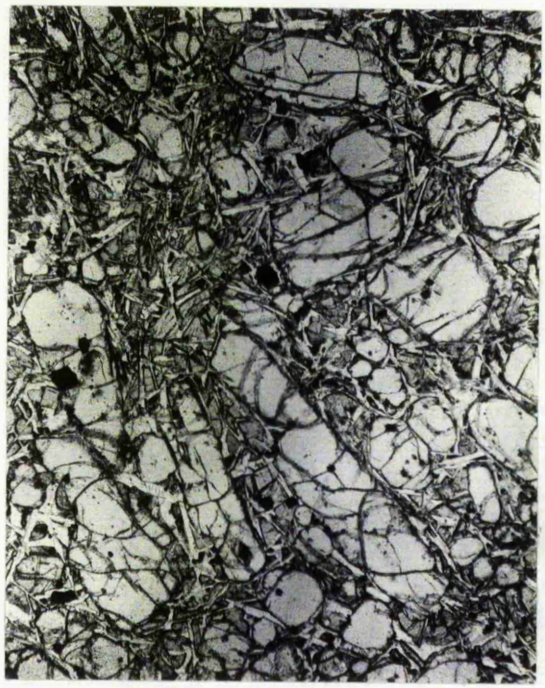
PLATE 3.

A.



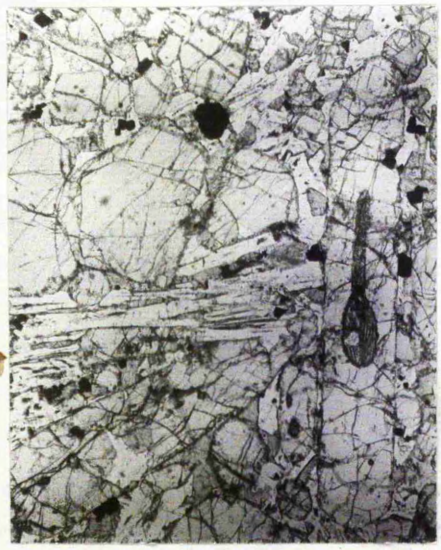
B.

PLATE 4.

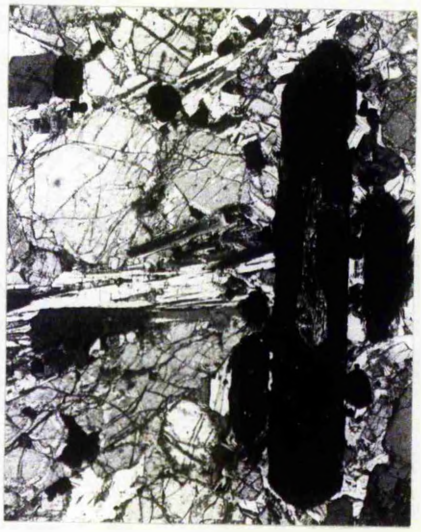


A.

B.



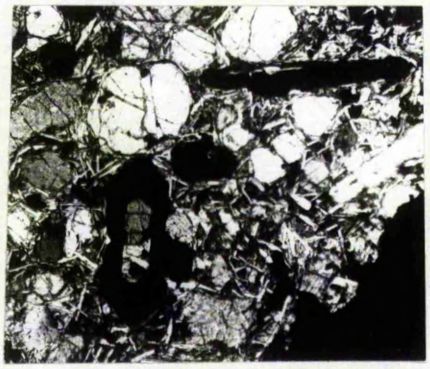
C.



D.

PLATE 5.

A.



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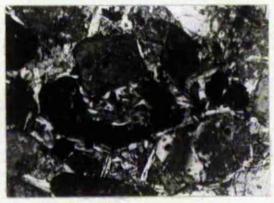
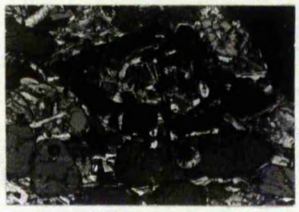


C.



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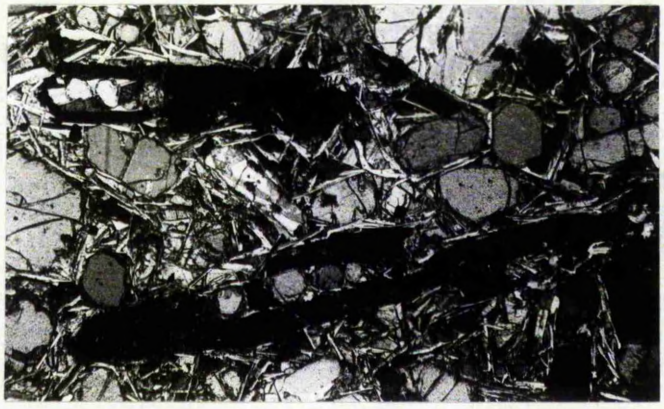

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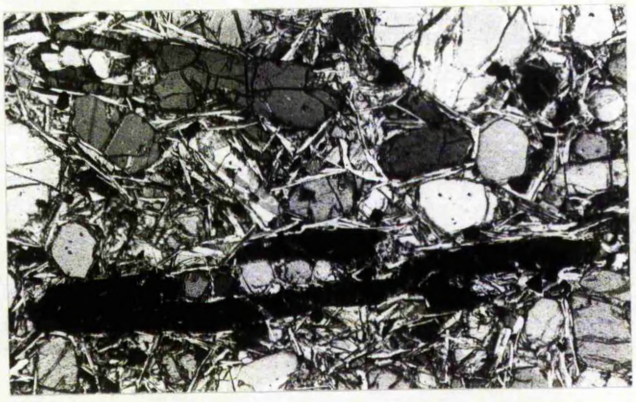
G.



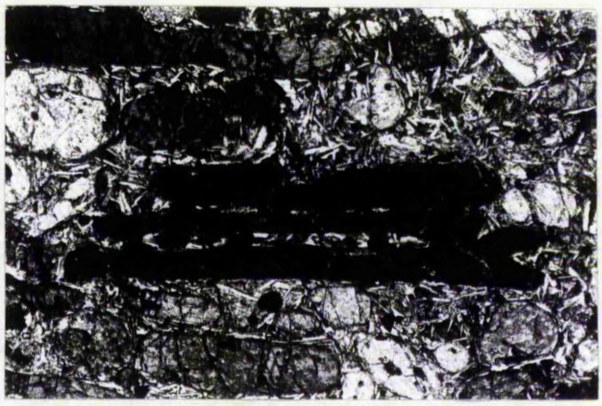
F.

H.

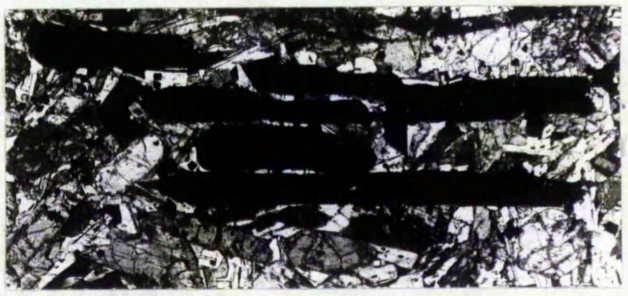
PLATE 6.

A.

B.



C.



D.

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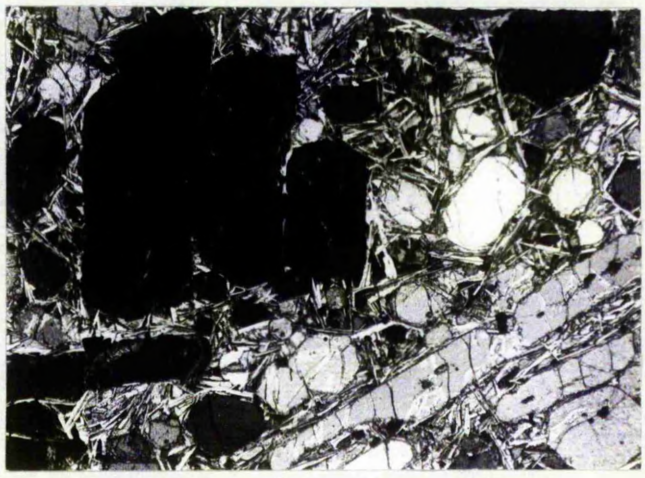

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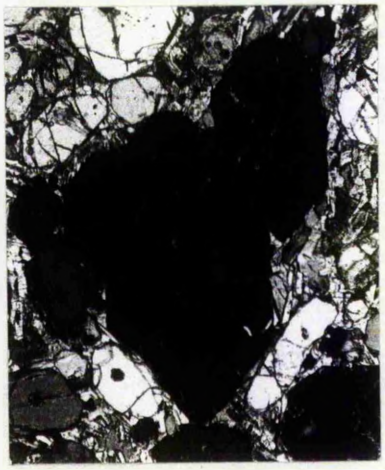

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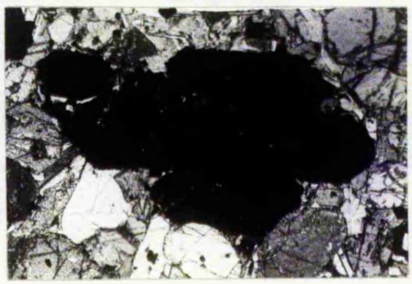


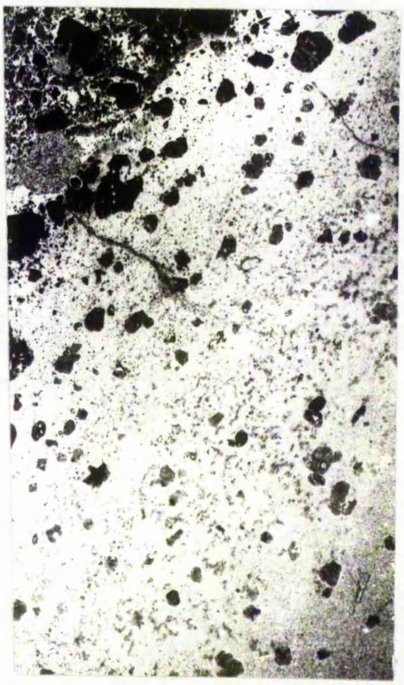
G.

PLATE 7.

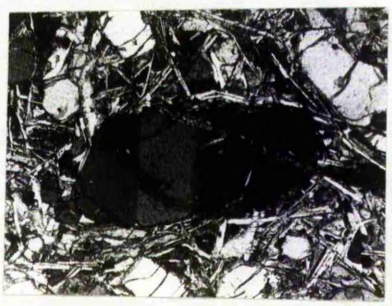
A.

B.

C.



D.



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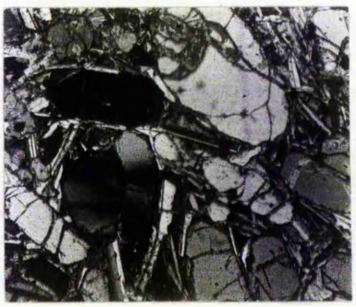


F.

PART II

THERMAL METAMORPHISM OF THE TORRIDONIAN SEDIMENT

1. INTRODUCTION

The general effects of the metamorphism and partial vitrification of the Torridonian sediments have been described in "Field Relations". With progressive metamorphism the sediment was selectively fused, and on cooling, the liquid produced by the fusion precipitated microlites of tridymite (now inverted to quartz), hypersthene, cordierite and magnetite. The remaining liquid finally quenched to a glass. The highest degree of metamorphism is illustrated by the black, obsidian-like xenoliths, contained by both sills, in which up to 92 per cent of the original minerals have been fused. The stages of fusion were traced by studying thin sections of specimens collected at various distances from Sill 1A, and the newly crystallized minerals were studied, in particular, in the glassy xenoliths. In the fine-grained metamorphosed sediment the products of fusion form a glassy matrix between corroded and partially fused grains. The matrix includes the quenched liquid, the decomposition products of original minerals and the new phases which crystallized from the liquid. It is crowded with microscopic crystals and the stages of fusion were not readily discernible, but in the coarser grained grits a clear picture was obtained of the order and manner in which the minerals of the original sediment were fused and incorporated into the matrix. In the basal contact zone of Sill 1A, there occurred hybridization between the picrite and the mobilized sediment, and resorbed olivine crystals are surrounded by the acid glass resulting from fusion of the sediment. Isolated olivine crystals and small picrite inclusions also occur in the glass of the rheomorphic vein. The fused xenoliths and the rheomorphic vein may be called buchites. Buchite was first defined as a fused sandstone, but its connotation was subsequently

extended to include all vitreous or semi-vitreous rocks produced by thermal metamorphism regardless of composition (Tomkeieff 1940).

Examples of the fusion of arenaceous rocks by basic igneous intrusions are fairly common but the writer could find no reference to fusion by ultrabasic rocks apart from the examples in Soay (Harker 1904, Clough and Harker 1904). From the rarity of fusion by ultrabasic intrusions compared to basic intrusions, it might be concluded that the latter are hotter than the former. It should be remembered, however, that ultrabasic minor intrusions are much rarer than similar basic intrusions. Moreover, many basic intrusions have not fused the sediments in contact with them when fusion might reasonably have been expected. For instance, the large Palisades sill of diabase contains xenoliths of arkose which show no signs of fusion (Walker 1940). Yet Sosman and Merwin (1913) demonstrated that, at atmospheric pressure, the arkose is more than half fused at 1150°C which is the temperature at which the diabase just begins to melt. They concluded that the unknown effect of the volatile ingredients of the magma modified the conditions considerably. Walker and Poldervaart (1949) appealed to favorable physical and chemical conditions to explain the localization of the fusion of sediments by the Karroo dolerites. The fusion of sediments by basic and ultrabasic intrusions may therefore be more dependent upon special conditions (for instance, the amount and nature of the volatile components of the magma and the sediment) than upon the actual temperature of the magma at the time of its intrusion. Recent experimental studies have demonstrated the remarkable effect of water vapour and other volatile components in promoting the crystallization or melting of silicate mixtures (Bowen and Tuttle 1950, Wyllie and Tuttle 1957).

The following account of the metamorphism is largely descriptive, and the petrographic evidence is discussed further in Part III.

2. THE ORIGINAL SEDIMENTS AND THEIR PROGRESSIVE METAMORPHISM

2.1. Petrography

Only one specimen was collected from the unmetamorphosed sediment below Sill 1A. The rock is fine-grained, even textured and red in colour. Sub-rounded clastic fragments consist mainly of strained quartz grains, turbid crystals of potash feldspar (orthoclase and microcline) and a small amount of plagioclase feldspar. The turbidity of the feldspar results from minute hematite inclusions. Grain size varies from 0.1 mm. to 0.2 mm. The quartz and feldspar grains are separated by sericite and siliceous cement containing much disseminated hematite dust. There are also several larger flakes of muscovite which are often bent. Magnetite occurs as disseminated dust and in larger grains which tend to be arrayed in lines parallel to the length of the larger muscovite flakes. The red colour of the rock is produced mainly by the finely disseminated hematite, although the feldspar also contributes. This one specimen is not representative of the country rock, because even in the vicinity of the sill there are variations in grain size, and probably in the proportions and compositions of the clastic grains. A general description of the country rock is given by Clough (Clough and Harker 1904) who describes the Beinn Bhreac group as:

> "Red and purplish-red false-bedded grits, most of them coarser than those in groups 1 and 3, and with abundant seams containing pebbles, from half an inch to two inches long, of quartzite felsite, andesite, and jasper. In most of the coarser grits the grains of feldspar and quartz are somewhat less than a small pea. Occasional thin bands of reddish and greenish sandy shale. Thickness about 2,200 ft." ....."The grits closely resemble those in the Applecross division on the mainland of Inverness-shire, but many of them are considerably coarser than most of those which are found in this division in the eastern part of Skye." ....."Specimens of grits from each of the groups have been examined by Dr. Flett, and each he finds to be highly feldspathic and to include orthoclase and microcline as well as, or in excess of, plagioclase."

TABLE 9. APPROXIMATE MODES OF METAMORPHOSED SEDIMENT

SPECIMEN	87	85	83	90	129
Quartz	54.0	65.5	49.0	20.0	8.0
Alkali feldspar	7.5	3.0	5.0	-	-
Plagioclase feldspar	1.0	0.3	-	-	-
Magnetite	7.0	10.0	6.0	4.0	-
Sericite	22.5	-	-	-	-
Siliceous cement	8.0	-	-	-	-
Glassy matrix	-	21.2	40.0	76.0	91.3
Rest	-	-	-	-	0.7

The progressive vitrification of the sediment with advancing metamorphism is illustrated by the approximate modal analyses listed in table 9. A Swift point counter was used, but the nature of the partially vitrified fine-grained sediment prohibited accurate determinations. Specimen 87 gives the volumetric proportions of the unaltered sediment 60 cms. below Sill 1A. The rock is a feldspathic sandstone, containing less feldspar than a normal arkose (Pettijohn 1949). It grades evenly upwards into black metamorphosed sediment, the change in colour resulting from the reduction of hematite to magnetite. 30 cms. below the basal contact zone, the only hematite remaining is that preserved within feldspar. The sericite is replaced by a dense glassy matrix, crowded with disseminated magnetite, which merges into siliceous cement. In specimen 85, 20 cms. below the basal contact zone, the glassy matrix constitutes

21.2 per cent of the rock, which compares closely with the proportion of sericite present in the unaltered sediment. The matrix is crowded with magnetite and many microscopic crystals, of which a few were tentatively identified as orthopyroxene and cordierite. Patches of the matrix are weakly birefringent. In this specimen there is 11.5 per cent more quartz than in the unaltered sediment. Many of the quartz grains are surrounded by rims of secondary quartz, which are believed to represent tridymite which crystallized from the interstitial liquid, subsequently inverted to quartz and then recrystallized. The secondary rims were included in the modal measurement of quartz, but they cannot account for the difference of 11.5 per cent. This demonstrates the variability of the sediment from one horizon to another. A contributory factor may be that some of the liquid migrated from its place of formation, leaving the residue relatively enriched in quartz. The mobility of the partially vitrified sediment is illustrated by the injection of fine-grained material into coarser grained and more rigid grit (plate 8A), and the movement of liquid from its place of formation is illustrated by the rheomorphic vein (plate 3B). Table 9 also shows an increase in magnetite and a decrease in feldspar for specimen 85 compared to specimen 87. This may result in part from the variability of the sediment, but petrographic examination confirms that the feldspar has been partially fused at this level. Other specimens from above and below Sill 1A are similar in general appearance to specimen 87.

The basal contact zone of Sill 1A comprises a mixture of black glassy rock, partially vitrified sediment, and masses of serpentinized picrite (plates 8C and D). The glassy matrix of the sediment is often brown in colour near the picrite, and it encloses isolated crystals of

olivine. The volumetric proportions of the constituents of this zone are extremely variable, and specimen 83 (table 9) was selected as representative of the least contaminated sediment. No inclusions of olivine or picrite were present in the thin section examined, and the glass was colourless. The percentages of quartz, feldspar and magnetite are smaller than in the original sediment, although the feldspar shows an increase over that in specimen 85, 20 cms. below the contact zone. The glassy matrix is much increased, amounting to 40 per cent of the rock.

The rheomorphic vein contains a much higher proportion of glass which is variable in amount from one specimen to another. Of the original minerals in specimen 90, only 20 per cent of rounded quartz grains remain, and these are generally surrounded by secondary quartz rims (plate 13D). Seventy-six per cent of the specimen consists of clear glass containing numerous microlites of hypersthene and cordierite, together with much magnetite dust; and 4 per cent consists of larger magnetite grains. In another specimen from the vein, small resorbed fragments of feldspar were found. Small inclusions of picrite and isolated olivine crystals, which are quite plentiful in the rheomorphic vein, were omitted from the modal determinations. It is unlikely that this vein corresponds to the original sediment in composition. A process of filter-pressing is suggested by variation in the amount of glass along the vein, and the material probably represents a fluid fraction separated from partially vitrified sediment near the basal contact zone, or from a fused xenolith near the base of the sill.

The xenolith of Sill 1 illustrates the most extreme fusion discovered (specimen 129, table 9, plate 9A). 91.3 per cent of this specimen

consists of glass containing microlites of cordierite, hypersthene, inverted tridymite and magnetite. Of the original minerals in the xenolith, only 8 per cent of rounded quartz grains remain and these are surrounded by fringes of inverted tridymite, plates 12A and B. In all sections examined less than 1 per cent of the rock consists of single, serpentinized olivine crystals. An expanded modal analysis of this specimen, giving in addition the percentages of the minerals which crystallized from the liquid, is listed in table 11. Although differential movement of solid and liquid material was probably involved in the injection of the rheomorphic vein, this xenolith must represent almost complete fusion in situ.

The elongated xenolith of buchite above the grit xenoliths (figure 4) is pale green in colour, in sharp contrast to the other black xenoliths. It contains very little magnetite and the colour is imparted by the green-tinted glass. Many of the remnant quartz grains have fringes of inverted tridymite, or secondary quartz rims, and some have isotropic borders outside the secondary quartz rims (plates 12C and D). These are formed of colourless glass which is separated from the green-tinted glass by sharp boundaries. A few small resorbed feldspar grains remain. Grains of carbonate (sometimes surrounded by narrow, colourless glass rims) and veins containing rosettes of carbonate occur sporadically throughout the xenolith. Locally, perfect rhombs of carbonate, less than 0.03 mms. in size, occur within the glass. Cordierite is present in small amounts and hypersthene is abundant. Hypersthene crystals may be prismatic in form, or they may be skeletal and extremely elongated (plate 12C). Some crystals, similar in morphology to the hypersthene, are pleochroic from green to yellowish green, and they exhibit oblique extinction. These

were tentatively identified as aegirine-augite. The rarity of magnetite, the colour of the glass, the relative abundance of carbonates and the presence of aegirine-augite suggest that this buchite was derived from sediment of bulk composition different from that of the other xenoliths.

From the modal analyses, it is clear that the development of liquid in the sediment resulted from decomposition of the sericite and the fusion of feldspar and quartz. This was confirmed by the petrographic study. Changes in the mineralogy of the sediment with progressive metamorphism and fusion may be illustrated in a qualitative way by x-ray powder diffraction patterns of selected rock specimens (figure 10). Patterns were recorded for the unaltered fine-grained sediment, for a glassy rim surrounding a grit xenolith and for the fused xenolith, specimen 129. In the unaltered sediment, peaks representing quartz, feldspar and muscovite are readily distinguished. Partial fusion of specimen 76 (figure 10B) has resulted in the disappearance of the muscovite peaks, a marked decrease in the intensity of the feldspar peaks and a decrease in intensity of the quartz peaks. Changes in the positions of the feldspar peaks will be discussed in section 2.2. In figure 10C, the presence of much glass is confirmed by the variation in the base of the diffraction pattern. No feldspar peaks remain, and the quartz peaks are much reduced in intensity. Small peaks representing cordierite and hypersthene can be distinguished, but peaks for magnetite occur outside the range of 2θ illustrated in the figure.

Examination of the modes and x-ray diffraction patterns of selected specimens are sufficient to establish the general behaviour of the fine-grained sediment in response to progressive metamorphism. Coarse-grained grits occur as irregular masses within the fine-grained

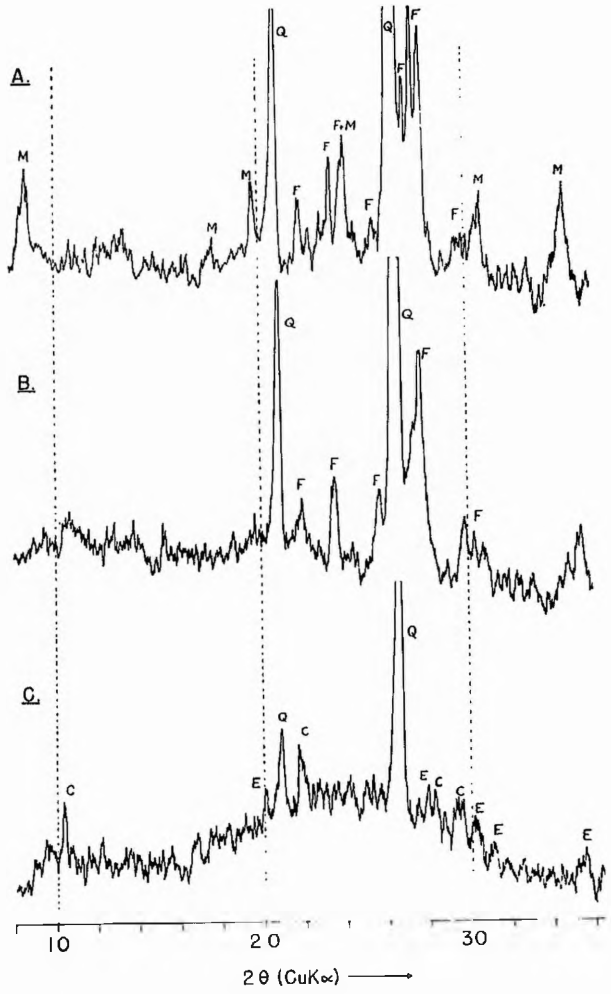


Figure 10. X-ray powder diffraction patterns of crushed rock specimens (scanning speed 2° per minute). A. Specimen 87, unaltered sediment. B. Specimen 76, buchite rim surrounding coarse-grained xenolith. C. Specimen 129, fused xenolith (see table 11). The peaks are marked by:- Q, quartz; F, feldspar; M, muscovite; C, cordierite; E, enstatite (or hypersthene).

sediment below the basal contact zone and as xenoliths within Sill 1A (figure 4, plate 9). The grits consist of large feldspar grains, smaller quartz grains and rounded pebbles of almost pure quartzite; these are enclosed by a glassy matrix which is variable in amount and distribution. The matrix is similar to that in the fine-grained sediments, but larger patches of clear glass are present. Magnetite is the only ore mineral in the matrix, but hematite has been preserved in many feldspar grains and in pebbles of quartzite, the component grains of which are cemented by siliceous material containing hematite dust. The hematite outlines quartz grains and forms parallel lines within the cement. Between crossed nicols the composite fragments appear as granular quartz with no distinction between original grains and cement except where hematite is present. Each grit xenolith is bordered by a band of black, fine-grained buchite, which separates it from the picrite. The band may be variable in width (plates 9B and C). Diffusion of volatile materials from the picrite into the xenoliths would aid the fluxing effect of the interstitial liquid, and this could explain why the edges of the xenoliths reached a more advanced stage of fusion than their centres. It is possible also that some of the interstitial liquid was squeezed out to the edges of the xenoliths. Some of the larger quartz grains have been fractured and slightly displaced, and the gap between the fragments is filled by a glassy matrix containing angular splinters of quartz. The xenolith must therefore have been subjected to stress sufficient to fracture the quartz at a stage when the xenolith was cooling, otherwise the irregular edges of the quartz splinters would have become rounded. The stresses could also have squeezed out the interstitial liquid .

Narrow veins traversing all the coarse-grained xenoliths demonstrate the circulation of hydrothermal solutions which postdated the consolidation of the fused sediments. The veins contain siliceous material, or carbonates, or both.

In the following section, more detailed descriptions are given of the manner in which the original minerals responded to the changing conditions accompanying the progressive metamorphism of the sediment.

2.2. Mineralogy

Sericite. Approaching the contact with Sill 1A, the first change noted in the sediment is the disappearance of sericite. Hydroxyl released by the decomposition of sericite would aid the fluxing action of the water vapour already present in the pores of the sediment and would hasten the formation of an interstitial melt. The additional effect of volatile materials escaping from the picrite will be discussed later. Many micas contain fluorine replacing hydroxyl (Yoder and Eugster 1954, Correns 1956) and the release of fluorine in addition to hydroxyl would enhance the fluxing properties of the interstitial material (Tuttle and Wyllie 1957).

Hematite. The change in colour of the sediment from red to black results partly from the production of a glassy matrix containing finely disseminated magnetite, and partly from the reduction of hematite to magnetite. The reduction is not a function of temperature alone, because hematite is preserved within feldspar crystals and quartzite pebbles in the xenoliths. The reduction of hematite to magnetite in

contact rocks is a common result of thermal metamorphism (e.g. Walker and Poldervaart 1949, Black 1954a), but because of the uncertainty regarding the partial pressure of oxygen in the circulating fluxes, the change cannot be used as a thermometer. The dependence of this reaction upon oxygen pressure is clearly displayed by Bastin's (1905) account of baked clays and natural slags in Eastern Wyoming. The widespread oxidation of iron in shales and sandstones has produced "gaudy colours" in the sediments, but in contact zones between argillite and slag, hematite has been reduced to magnetite. Elsewhere, sandstone passes into a glassy mass enclosing minute crystals of hematite.

Feldspar. Incipient fusion of the alkali feldspar is apparent in specimen 85, 20 cms. below the basal contact zone, and the degree of fusion increases as the base of the sill is approached. In the glassy xenoliths, feldspar is rare or absent. Incorporation of the feldspar into the interstitial melt is a dual process, resulting from direct fusion and from mechanical disintegration. Not only is the feldspar marginally dissolved, but thin seams of liquid develop also along cleavage planes (plate 10). When the feldspar is traversed throughout by liquid veins it illustrates the "finger-print" structure described by Guppy and Hawkes (1925), Tidmarsh (1932), Davidson (1935) and Allison (1936). At this stage, the feldspar crystals in plane polarized light are barely distinguishable from the glassy matrix. Many of the crystals retain their integrity, but others are broken into small cleavage fragments which become dispersed in the liquid (Lacroix 1893, Knopf 1938, Larsen and Switzer 1939). The optical continuity of the separated feldspar fragments in plates 10C and D does not confirm the evidence

presented earlier that the vitrified sediment was very mobile. Enrichment of the interstitial liquid in feldspathic material probably produced local areas of high viscosity (Day and Allen 1905). The plagioclase feldspar undoubtedly behaved similarly (Allison 1936), but its amount is too small for the stages of fusion to be traced. In the clear glass of the rheomorphic vein a few feldspar fragments are represented by small, rounded aggregates of rectangular cleavage fragments, still in optical continuity. One of the aggregates retains albite twinning. Some of the larger feldspar grains in the coarser sediments are bordered by narrow, colourless rims which may represent a new growth of feldspar (Richarz 1924, Tidmarsh 1932).

It is well established from the work of Spencer (1937) and others (e.g. Mackenzie and Smith 1956) that when feldspars are heated they undergo structural changes which result in changes in optical and x-ray properties. Prolonged heating at 1050°C will sanidinize most alkali feldspars, causing 2V to decrease to 0° and to increase again in a plane parallel to (010) (Spencer 1937). At least three types of feldspar, microcline, orthoclase and plagioclase, are present in the unaltered sediment, and it is probable that their proportions and compositions vary from one stratigraphic horizon to another. Anorthoclase may occur as well (see below), but its presence was not confirmed. It is impossible, therefore, to relate studies of feldspars in the fused rocks to known starting materials. No microscopic unmixing of the feldspars was detected either in the unaltered sediment or in the fused sediments, and cross hatched twinning in alkali feldspars and albite twinning in plagioclase feldspars persists in the fused sediments.

According to Tuttle (1952), the optic axial angle is the most useful

optical property for the classification of alkali feldspars. Values of 2V for several homogeneous feldspars within a coarse grit xenolith were therefore measured on the universal stage. The measured crystals are small compared to the large, twinned crystals which are more characteristic of the partially fused grit. Both single and double axis methods were employed, and the accuracy of measurements is about $\pm 3^{\circ}$. The conoscopic method could not be used owing to the diffuseness of the isogyres.

In six of the nine feldspars measured, one or two cleavages were distinguished. The better cleavage was taken as the (001) plane. Values of (-)2V obtained were: (1) triclinic; 63°, 76°, 78°, (2) monoclinic; 32°, 40°, 42°, and (3) no cleavage found; 40°, 45° and 48°. The optic axial plane is perpendicular to (010) in the monoclinic feldspars and approximately perpendicular to (010) in the triclinic feldspars. Limited conclusions may be reached concerning the nature of the feldspars by comparing these results with the diagram of Mackenzie and Smith (1955), modified after Tuttle (1952). (1) The triclinic crystals are probably intermediate microclines; (2) the monoclinic crystals could be (a) orthoclase in the composition range Or_{88} to Or_{100}, or (b) sanidine in the composition range Or_{35} to Or_{65}; (3) the crystals with no cleavage could be (a) orthoclase in the composition range Or_{80} to Or_{90}, (b) anorthoclase in the composition range Or_{15} to Or_{35}, or (c) high sanidine in the composition range Or_{85} to Or_{90}. The feldspars in the xenolith may therefore include intermediate microcline, orthoclase, anorthoclase and sanidine. Since microcline is present, the occurrence of high sanidine appears to be improbable, especially as none of the crystals with cleavages has its optic axial plane parallel to (010), (high sanidines are rare in nature, Mackenzie and Smith 1955).

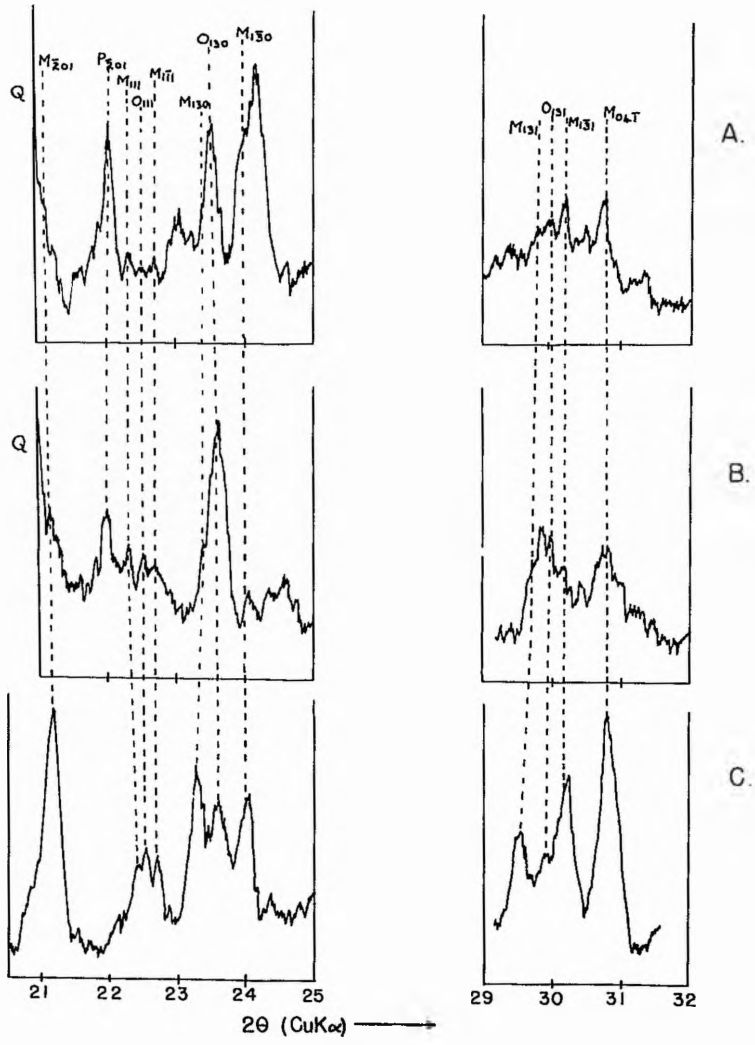


Figure 11. X-ray powder diffraction patterns of crushed rock samples, and of a feldspar prised from sediment (scanning speed 0.25° per minute). A. Specimen 87, unaltered sediment. B. Specimen 76, buchite rim surrounding coarse-grained xenolith. C. Feldspar prised from the grit xenolith, specimen 76. Feldspar peaks are indicated by:- P, plagioclase feldspar; M, microcline; O, orthoclase (or possibly sanidine). Q is a quartz peak.

Many of the large feldspar crystals within the xenolith contain cross-hatch twinning, and one of these was prised from the specimen. Its x-ray powder pattern covering the ranges of 2θ which provide information about the composition and structural state of feldspars, is given in figure 11C. Using figure 11C, the estimated composition of the feldspar is Or_{79} (estimated from the $\bar{2}01$ spacing, with Lake Toxaway quartz as an internal standard; Bowen and Tuttle 1950). The pattern is almost identical with the one given by Mackenzie (1954, figure 5a), in which orthoclase co-exists with microcline in a single crystal. The spacing between the 130 and $1\bar{3}0$ peaks of the microcline indicates nearly maximum departure from monoclinic symmetry. The absence of structural states intermediate between maximum microcline and orthoclase suggests that the orthoclase was not produced by the action of heat on microcline, but was present before fusion of the sediment.

Portions of the x-ray powder diffraction patterns shown in figure 10 are reproduced in figures 11A and 11B. The patterns cannot be simply interpreted, because more than one feldspar is present in addition to other minerals. In the unaltered sediment, specimen 87 (figure 11A), $\bar{2}01$ peaks for potassic feldspars are present, although almost obliterated by the strong quartz peak. The peak near 22° is outside the range of $\bar{2}01$ for alkali feldspars (Bowen and Tuttle 1950) and probably represents the $\bar{2}01$ peak for plagioclase feldspar. Its intensity suggests that the percentage of plagioclase feldspar in the sediment is greater than estimated by modal analysis, table 9 (all untwinned feldspar was allocated to alkali feldspar in the modal determinations and it is probable that some untwinned plagioclase was included. Another possibility is that

the proportion of plagioclase feldspar varies within a single specimen, as well as from one horizon to another). The subsidiary peak just below $2\theta = 22^{\circ}$ suggests the presence of anorthoclase. Several of the other feldspar peaks are superimposed on each other and further complicated by the presence of muscovite peaks.

The pattern for specimen 76 (figure 11B) is simpler because no muscovite remains in this specimen, the buchite rim surrounding a grit xenolith. The plagioclase $\bar{2}01$ peak is reduced in intensity relative to the alkali feldspar peaks, confirming that the proportion of plagioclase in the sediments is variable. Microcline and possibly anorthoclase are present, but the 130 peak for orthoclase is dominant. This could indicate that: (1) the proportion of orthoclase exceeded that of microcline in this buchite before fusion, or (2) original microcline was converted to orthoclase or sanidine. The nature of the 130, 131, and $1\bar{3}1$ peaks indicates intermediate states between maximum microcline and orthoclase, so it may be tentatively concluded that original microcline has been partially converted to orthoclase and sanidine.

The buchite examined (specimen 76) surrounds the coarse grit xenolith in which the feldspar 2V measurements were made. It is probable that the feldspars in the fine-grained buchite have responded structurally to the heating produced by the picrite, and some structural adjustment may also have occurred in the homogeneous feldspars examined optically within the coarse xenolith. The x-ray pattern for one of the large twinned feldspars within the xenolith (figure 11C) indicates no structural response to the heating. The smaller feldspars in the xenolith and those in the buchite rim around the xenolith are more closely associated with the glassy matrix than the larger feldspars, and if there is a

difference in response between them, it may have resulted from the fluxing action of the greater concentration of liquid (with its dissolved volatiles) on the smaller feldspars. The sanidinization of alkali feldspars in fused xenoliths enclosed by basic rocks has been recorded (Lacroix 1893, 1908, Richarz 1924) but the process of sanidinization is imperfectly understood. Some feldspars resist change even when heated for very long periods (Mackenzie and Smith 1956). Failure of the feldspars to adjust structurally might be due to rapid cooling, with insufficient time at elevated temperatures. Studies by Mackenzie (1957) of changes in the lattice parameters of albite confirm that: (1) extremely long periods of time are required to produce structural changes either in natural low temperature albite or in synthetic (high) albite, except at temperatures near the melting point, and (2) the presence of water vapour under pressure promotes structural changes in albite at low temperatures, although a long time is required for the attainment of equilibrium.

Quartz. Rounded and embayed quartz grains occurring below the basal contact zone confirm that the quartz began to fuse at an early stage of the metamorphism. Fusion undoubtedly resulted from fluxing by the interstitial liquid, and from mutual fluxing wherever quartz and feldspar grains were in contact (Thomas 1922, Allison 1936, Knopf 1938). The behaviour of the quartzite pebbles in the coarser grained sediments confirms the importance of interstitial fluxing material in the development of a liquid from minerals with high melting points. Where no passageways were available for the transit of fluxes no liquid developed. The boundaries between quartzite pebbles and the glassy matrix of the grits are sharp and smoothly rounded, cutting across both original quartz

grains and siliceous cement, and the pebbles fused as if they were single crystals. There is no glass within them, and no evidence that tridymite was ever developed. Tridymite was precipitated from the interstitial melt on cooling with the formation of fringes around the resorbed quartz grains, and this raises the question of why the quartz grains themselves did not change to tridymite. The probable reason is given in Part III. Although the transition from quartz to tridymite is sluggish, tridymite crystallizes readily from liquids in the presence of water vapour under pressure (in its stability field). The volatile materials within the interstitial liquid had access only to the margins of the quartz grains and of the quartzite pebbles, and therefore could not be very effective in promoting their inversion to tridymite.

Magnetite. The modal analyses of table 9 confirm that the iron oxide originally present in the sediment dissolved in the interstitial melt, but the presence of euhedral crystals of magnetite in the buchites indicates that magnetite later recrystallized. No way of distinguishing with certainty between remnant and newly crystallized magnetite was found. Harker (1904) concluded that all of the iron ore present in the Torridonian sediments was dissolved during fusion by basic sills in Soay, and it is probable that the same was true here.

3. THE PRODUCTS OF METAMORPHISM AND FUSION

Selective fusion of the original minerals in the sediment produced a liquid which, on cooling, precipitated the minerals tridymite, cordierite, hypersthene and magnetite. Further cooling quenched the liquid to a glass in which the new minerals were preserved, although the tridymite subsequently inverted to quartz. Descriptions of the new phases are given below.

3.1. Glass

The transition of the red, fine-grained sediment into the black metamorphosed sediment is accompanied by the appearance of a dense, extremely fine-grained matrix containing glass. The matrix resulted from the decomposition and selective fusion of the original minerals but its fine-grained nature prevented a detailed petrographic study of its constituents. The proportion of the glassy matrix in the sediment increases towards the basal contact zone, and here it amounts to about 40 per cent of the vitrified sediment. After the decomposition of the sericite in the original sediment, the initial liquid probably developed by the attack of the interstitial fluxes on feldspar and quartz. The fusion of quartz and feldspar at junctions between the two minerals, with the formation of a low temperature liquid, has often been described (Allison 1936, Knopf 1938) and the development of such liquids has also been explained by the selective fusion of feldspar, followed by solution of quartz in the feldspathic melt (Thomas 1922, Osborne 1950). Consideration of phase equilibrium studies (Part III) confirms that both processes are applicable. Quartz and feldspar in contact would produce a low temperature liquid by mutual fluxing and, once such a liquid is present,

both quartz and feldspar would dissolve in it.

Macgregor and Wilson (1939) estimated that if a rock composed of spherical grains contains 26 per cent of liquid, it will become mobile. The degree of fluidity will depend, of course, not only upon the proportion of liquid present but also upon the viscosity of the liquid. The viscosity of the liquid must have been reduced considerably by its high water content, and the mobility of the vitrified sediment is clear from plate 8A and from the existence of a glassy rheomorphic vein (plate 3B). The viscosity of feldspathic liquids appears to have remained high (plate 10D). The coarse-grained xenoliths contain less glass than the fine-grained xenoliths, but the ubiquitous presence of black glassy rims between the grit xenoliths and the enclosing picrite suggests that much of the interstitial liquid was squeezed out from between the coarser clastic grains. Marginal concentration of volatiles from the picrite may have increased the extent of fusion at the edges of the xenoliths. The black, obsidian-like xenoliths occurring in both sills (plate 1B and figure 4) have been almost completely fused, and they consist of clear, colourless glass containing resorbed grains of quartz, a few inclusions of olivine pseudomorphs, and the new minerals which crystallized from the melt (plates 11 and 12). In one xenolith, the glass has a green tint. The proportion of the glassy matrix in the rheomorphic vein is almost as great as in the fused xenoliths, but the preservation of a few small feldspar grains indicates an earlier stage of fusion than that represented by the buchite xenoliths. The glass in the rheomorphic vein is colourless and, although it encloses small, discrete inclusions of picrite, it has not sufferred obvious contamination by igneous material (plate 13).

TABLE 10. CHEMICAL ANALYSIS OF A FUSED XENOLITH COMPARED WITH OTHER ANALYSES OF GLASSES PRODUCED BY FUSION

	1	2	3	4	5
SiO_2	71.04	71.90	69.72	72.57	71.29
Al_2O_3	10.92	12.45	14.80	13.08	12.69
Fe_2O_3	2.14	-	0.55	0.94	1.22
FeO	1.48	-	1.36	0.50	0.69
MgO	2.22	-	0.40	0.08	0.41
CaO	1.34	1.89	1.42	1.12	0.77
BaO	-	-	0.05	0.08	-
Na_2O	2.96	4.18	3.87	3.75	4.19
K_2O	1.35	1.91	2.75	2.33	3.54
H_2O	4.48	6.32	4.33	5.21	4.57
H_2O -	0.52	-	0.15	0.17	-
TiO_2	0.68	-	0.48	0.18	0.29
MnO	0.07	-	0.13	0.02	-
P_2O_5	0.96	1.35	0.21	0.23	-
	100.16	100.00	100.22	100.26	99.66
Refractive index		1.502	1.505	1.501	1.497
Specific gravity			2.37	2.35	2.40

1. Fused xenolith, specimen 129, Sill 1A. Analyst: W.H.Herdsman (New Series).
2. Calculated composition of the glass in the fused xenolith, specimen 129. Analysis 1, less remnant quartz and inverted tridymite, less 4 per cent normative enstatite, remaining MgO subtracted as cordierite and all iron and titania subtracted as normative ore minerals.
3. Calculated composition of glass in fused xenolith of feldspathic sandstone. Analyst: J.J.Frankel (from Frankel 1950, Coldbrook glass).
4. Glass separated from fused xenolith of feldspathic sandstone. Analyst: J.J.Frankel (from Frankel 1950, Ecca grit).
5. Glass separated from fused xenolith of tonalite. Analyst: G. Switzer (from Larsen and Switzer 1939).

TABLE 11. COMPARISON OF THE NORM AND MODE OF THE ANALYZED FUSED XENOLITH

NORM		MODE	
q	45.3	Quartz	8.0
or	7.8	Glass	66.5
ab	25.2	Cordierite	7.5
an	0.3	Hypersthene	5.8
co	4.5	Inverted tridymite	6.5
hy (en)	5.6	Magnetite	5.0
mt	3.0	Olivine	0.7
il	1.4		100.0
ap	2.4	Glass plus new minerals	91.3
H_2O	5.0		

The chemical analysis of the most highly fused xenolith found (specimen 129, Sill 1) and the calculated composition of the glass within the xenolith are listed in table 10. Analyses of glasses in fused xenoliths from other localities are included for comparison. The relatively high content of MgO in the fused xenolith (compare the other analyses, and analysis 5, table 12) is probably due in part to the presence of olivine xenocrysts. The norm of the fused xenolith, and a modal analysis are given in table 11 (compare table 9). The modal percentages of cordierite, hypersthene and magnetite have undoubtedly been overestimated, because many of these crystals are thinner than the slide containing them (0.03 mm.) and some allowance has been made for

this in calculating the composition of the glass. Inverted tridymite was similarly overestimated but since this mineral is densely packed around quartz grains (plate 12A) the error is smaller. The specific gravities of the minerals involved in the calculations were obtained from Winchell and Winchell (1951) and that of the glass was assumed to be 2.38 (see table 10). The method of calculation is given in table 10, and it is clear that the calculated analysis of the glass is only an approximation. However, as shown in Part III, the analysis probably represents the glass fairly accurately in its major constituents. Despite the approximate nature of the calculation, the result agrees quite well with the analyses of similar glasses presented by Frankel (1950) and by Larsen and Switzer (1939).

The fused xenolith contains a high proportion of water, and most of this is concentrated in the glass (cf. Harker 1950). The glass also contains 1.35 per cent of P_2O_5. The other analyses in table 10 are characterized by high water content, and there is no doubt that abundant volatile materials were available during the fusion of these rocks.

The volatiles must have been derived either from the sediment or from the picrite. The average analysis of Torridonian sediment in south-eastern Skye (see table 12) contains only 1.06 per cent of water and 0.30 per cent of P_2O_5. The sediment in the neighbourhood of Sills 1 and 1A probably contains more mica than the average Torridonian sediment but, even so, the high proportion of volatile material contained by the fused xenolith, which is completely surrounded by picrite, could hardly have been present initially in the sediment and it appears certain that most of the volatiles emanated from the picrite. Larsen and Switzer (1939) similarly concluded that only the fluxing action of large

quantities of water from olivine basalt magma made possible the fusion of a tonalite xenolith in the basalt. Walker and Poldervaart (1949) believed that chloride and sulphate ions in the sediments were responsible for the local fusion and mobilization of sediments produced by the Karroo intrusions, but the presence of such ions was not established and their efficacy as fluxing agents is not known. Later analyses of sediments fused by the Karroo intrusions (Frankel 1950, table 10) reveal a high water content, and the fluxing action of the water probably caused the fusion.

Samples of glass free from inclusions could not be obtained for specific gravity measurements, but refractive indices were determined in sodium light on crushed fragments (±0.003): (1) Glass of the analysed xenolith (specimen 129), n = 1.502; (2) Glass in the rheomorphic vein, n = 1.500; (3) Glass in the green tinted buchite, n = 1.482.

Since silica is the most abundant oxide in natural glasses, it might be expected that the refractive indices and specific gravity of glasses should show some relationship to their silica content. Stark (1904) and George (1924) attempted such correlations. George also attempted to correlate the percentages of magnesia, lime, iron oxides, potash and water (water from specific gravity only). He concluded boldly that his curves would provide rapid and fairly accurate estimates of the compositions of natural glasses. Tilley (1922) regarded such relationships, even for the dominant oxide silica, as no more than rough approximations on the grounds that each constituent of a glass would contribute its effect, and the refractive indices of two glasses with the same silica percentage might therefore be quite different. He demonstrated convincingly that the water content of a glass has a

Coarse limestone with fossil structures. Distinguish between cloudy c and clear dolomite.

K. Shelly Limestone. N. Leicestershire.

Note abundant sections through shell structures of brachiopods (or lamellibranchs) and foraminifera.

L. Chalk. Inaceramus bed, Yorkshire.

Fine-grained calcareous mud with abundant round sections of calcareous algae and larger shell fragments.

significant effect on its refractive index.

Several glasses developed in xenoliths have been analyzed since 1924 (Holmes 1936, Larsen and Switzer 1939, Frankel 1950, analysis 2 table 10) and, using George's (1924) curves, their chemical compositions were estimated from their determined refractive indices and specific gravities. Although Frankel (1950) considers that his results showed fair agreement with George's curves, agreement of the estimated percentage of any particular oxide with the chemical analyses of the various glasses appeared to be quite fortuitous, and the errors obtained were not consistent. The error in silica percentage varied from 1 to 10 per cent, and potash was constantly in error by plus or minus 1 or 2 per cent. Mathews (1951) proved that the refractive indices of glasses produced by artificial fusion of samples from selected suites of igneous rocks show a close correlation with their chemical composition. The fusion eliminates water and converts all iron to the ferric state. In special circumstances, therefore, the refractive indices of glasses may give useful information concerning their compositions (see also Jicha 1955), but any estimate of the composition of glasses (2) and (3) above on the basis of their refractive indices is considered unjustifiable.

3.2 New Minerals

Tridymite. Surrounding resorbed quartz grains in the fused xenoliths and the rheomorphic vein are fringes of small colourless prismatic crystals which extend at all angles from the grains (plates 12A and B). The fringes are composed of quartz in optical continuity with the grains to which they are attached. Similar fringes occur frequently in fused

siliceous rocks and they have been described by Lacroix (1893), Thomas (1922), Campbell et alia (1933), Holmes (1936), Tomkeieff (1940), Walker and Poldervaart (1949), Frankel (1950) and Osborne (1950). They are particularly well developed in xenoliths occurring within the Tertiary igneous rocks of Scotland (see, for example, Bailey et alia 1924). Reynolds (1940) described the development of similar fringes without the intervention of an interstitial melt, but noted that passageways for the movement of fluxes were necessary for their formation. Minute crystals with the same habit, associated also with hexagonal flakes, may be preserved within a glass or within feldspar crystals (Reynolds 1908, Thomas 1922, Holmes 1936, Knopf 1938, Harker 1950, Osborne 1950, Wells 1951). Flett (1911) believed that the fringes were possibly due to penetration of the melt along rhombohedral cleavages of the quartz, and Tomkeieff (1940) thought that they might possibly represent inverted cristobalite. All other investigators are agreed that they represent inverted tridymite, and the preservation of tridymite in some of these occurrences confirms this conclusion (Lacroix 1908, Knopf 1938, Osborne 1950).

Standard text books of mineralogy, e.g. Winchell and Winchell (1951), describe tridymite in wedge shaped crystals or six-sided thin tabular crystals, commonly showing twinning, but no mention is made of prismatic crystals. From synthetic melts tridymite invariably crystallizes as thin, six-sided plates (e.g. Bowen 1914), and the development of a prismatic habit appears to be restricted to tridymite which grew from natural melts.

Many quartz grains in the partially fused sediments are surrounded by a secondary rim of quartz (plates 12D and 13D). The outer edge of

the rim may be well defined or it may merge into the glassy matrix. In several examples from the buchites, the fringes composed of distinct prismatic crystals pass into continuous rims of homogeneous quartz. The gradation from fringe to rim around a single quartz grain is often quite clear, and the rims of secondary quartz may be confidently attributed to the inversion and recrystallization of original tridymite fringes. Lacroix (1908) recorded the inversion of many small tridymite lamellae into a sponge of quartz in optical continuity, and Hawkes (1916) described examples where one or more tridymite plates inverted and recrystallized into a homogeneous quartz grain. Single tridymite crystals are also known to invert into an aggregate of smaller quartz crystals (Mallard 1890, Hawkes 1916, Wager et alia 1953).

Cordierite. Minute, colourless, six-sided prisms of cordierite have crystallized from the partially vitrified sediment (plate 11). They are most plentiful in the glassy xenoliths and it is here that their form may be clearly distinguished. A few crystals attain lengths of 0.06 mms. but most are considerably smaller. Their optical properties agree with those of the microscopic cordierites which characteristically occur in fused sandstones and shales. Most crystals form simple prisms but parallel growth of somewhat elongated crystals may produce "stepped" edges to the prismatic faces (plate 11D). In cross section such crystals appear as overlapping hexagons (plates 11A and 11C). Parallel growth in synthetic cordierite was described by Shand (1943). Some crystals have short extensions to their prismatic faces indicating a tendency toward skeletal crystallization (plate 13B). Venkatesh (1952) described in detail the more extreme skeletal crystallization of microscopic

cordierites occurring in sediments fused by burning coal seams. The edges of all cordierite crystals are clear while their central parts contain inclusions of dusty magnetite, which are arranged parallel to the length of the crystals and which appear as cores in cross sections. Similar inclusions of spinel or iron ore are common (Prohaska 1885, Zirkel 1891, Venkatesh 1952). In the glass surrounding many cordierite crystals there are cracks either approximately following the crystal boundaries (plate 11C) (cf. Zirkel 1891), or approximately perpendicular to crystal edges (plate 11D). The cracks probably developed during cooling by contraction of the glass away from the cordierite.

Even with very fine crushing it was impossible to obtain crystals free from glass and it could be determined only that the refractive indices of the cordierite are near to 1.53. All prismatic sections have straight extinction and most are length fast. The few which are length slow probably represent very short prisms with the diameter of the basal pinacoid greater than the length of the prism faces (Prohaska 1885, Zirkel 1891). Pseudohexagonal sections are almost isotropic but in some sections sector twinning is visible. The twinning can be seen more clearly if the mineral is viewed in sodium light with a one wave-length retardation plate inserted (plate 11B). There are six triangular sectors with opposite pairs in optical continuity. The slow vibration direction in each sector is perpendicular to the side of the prism face, and (110) is therefore the twin plane and composition plane (Venkatesh 1954). The optic axial plane is perpendicular to the prism face in each sector and the optic orientation of the twinned crystals is that illustrated in Winchell and Winchell (1951, figure 364). Attempts to measure 2V on the universal stage were unsuccessful but (-)2V must be

small because basal sections are almost isotropic. Sector twinning in microscopic cordierite was recorded by Prohaska (1885), Zirkel (1891), Craig et alia (1911), Bailey and Wright (1924), and more complicated cyclic twinning was described in detail by Hussak (1883) and Venkatesh (1954). Venkatesh suggested that the type of twinning in cordierite bears some relationship to the nature of the host rock. Complex twinning has been observed only in fused rocks and in synthetic crystals, and he therefore regarded it as characteristic of cordierite formed in high temperature melts. However, simple sector twinning alone is common in high temperature melts as indicated by the examples quoted above, so the absence of cyclic twinning and the prevalence of sector twinning does not imply that the cordierite crystallized at a low temperature. Miyashiro (1957) concluded that complex twinning may result from varying distortion of the lattice in different parts of a single crystal.

At least one crystal in the fused xenolith has the shape of an interpenetrant cross. The use of a one wave length retardation plate renders the twin units clearly visible (plates 12D, E and F). Two other crystals were found which appeared similar (plate 11C), but they were too small for details to be distinguished. On the universal stage the approximate positions of two optic symmetry planes, both containing the 'c' axis, were determined for each twin unit. It could not be decided which of these was the optic axial plan because no optic axes were found. From stereographic projection of the data the best estimate of the twin plane is either (021) or (101), depending upon which of the optic symmetry planes is the optic axial plane. According to Winchell and Winchell (1951) and Venkatesh (1954), twinning in cordierite is

exclusively confined to the (110) and (130) planes, so this is an unreported twin plane for cordierite. In recent hydrothermal experiments on the fusion of shales (Wyllie and Tuttle 1958), the writer has found cordierite crystals which appear to be twinned according to the same law.

Iron and manganese are known to substitute for magnesium in cordierite. Bücking (1900) found iron cordierite in fused xenoliths and Fermor (1924) concluded that the cordierites in the paralavas of India were iron rich. The microscopic cordierites described by Zirkel (1891), Bastin (1905) and Fermor (1924) are violet in colour, and pleochroic. Fermor suggested that colour in cordierite is due to a high content of iron but Krishnan (1924) doubted this, believing that the colour was more probably due to traces of manganese. Richardson and Rigby (1949) and Schairer and Yagi (1952) published x-ray data for synthetic magnesian and iron cordierites, but the interpretation of this data requires revision because of the discovery that minerals of cordierite composition exist in several structural modifications (Miyashiro et alia 1955). A new high temperature hexagonal mineral, indialite, was discovered in the fused rocks described by Venkatesh (1952, 1954) and Miyashiro (1957) later concluded that all gradations exist between indialite and cordierite. He distinguished between subdistortional and perdistortional cordierite, according to the degree of distortion of the hexagonal lattice. The relations are further complicated by the existence of high and low forms in each modification. The orthorhombic symmetry of the cordierite in the fused xenolith of Sill 1 is confirmed by the multiple peak occuring between $2\theta = 29^{\circ}$ and 30° in the x-ray powder pattern of figure 10C, but the cordierite peaks are too

small to permit an estimate of its structural state (Miyashiro 1957). According to Iijama (1956) there is no simple relation between the optical properties and the compositions of cordierites unless special attention is paid to structural relationships. However, since (-)2V is small the degree of distortion of the hexagonal lattice is small and the mineral is probably a subdistortional cordierite which is stable at high temperatures. No estimate of composition can be made from the available optical data. Comparison of the mode and the chemical analysis of specimen 129 (tables 10 and 11) suggests that the cordierite is magnesian, because the amount of iron present is barely sufficient to account for the magnetite. The absence of colour in the cordierite is tentatively adduced to support this conclusion.

It is generally agreed that the formation of cordierite in fused siliceous rocks requires the mixing of basic magma with the fused material, or at least an accession of magnesia from the magma (Prohaska 1885, Zirkel 1891, Harker 1904, Thomas 1922, Bailey and Wright 1924). Contamination of the fused products is often revealed by brown colouration of the glass (e.g. Harker 1904, Frankel 1950) but when cordierite occurs in colourless glass accession of magnesia is not necessarily indicated, although it is likely in the case of the fused xenolith in Sill 1 (table 10). If the growth of cordierite depended upon the accession of magnesia from the igneous rock, it might be expected that the proportion of cordierite would increase as the intensity of colour in the glass increased. This is not so near Sill 1A, nor in the examples described by Harker (1904). The greatest development of cordierite is not in the brown glass of the basal contact zone but in the colourless glass of the xenoliths and rheomorphic vein. Provided some magnesia was present in

in the original material cordierite would be expected to grow as a product of simple fusion and recrystallization (cf. Richarz 1924, Venkatesh 1952). Tridymite, hypersthene and cordierite consitute a stable metamorphic assemblage at high temperatures in rocks with appropriate bulk composition (Tilley 1923).

Hypersthene. Small accicular crystals are developed wherever glass is plentiful. The crystals are almost colourless but sometimes exhibit weak yellowish-green pleochroism. Rhombic cross sections are brownish in colour. All elongated sections show straight extinction, with the slow vibration direction parallel to the length. In crushed samples the accicular crystals projected from fragments of glass and it was established that the refractive indices α and γ lie between 1.670 and 1.680 ($\pm$ 0.003). 2V was measured on the universal stage and found to be near 90^{o}. The optical properties accord with those of orthopyroxene and they indicate a composition in the range Fs_{15} to Fs_{20} (Kuno 1954).

The most striking features of the crystals are their great elongation and their skeletal form. Rapid growth rate in the direction of elongation has produced deep, funnel shaped hollows in the prism terminations. In plate 12C the hollow in one crystal persists throughout its visible length. Locally developed are shorter crystals, with well defined funnels at each end (plate 12A). Similar skeletal growths of microscopic hypersthene in buchites were described in detail by Rinne (1895). Orthopyroxene does not appear in buchites as often as clinopyroxene, but skeletal crystals of hypersthene have been reported by Lacroix (1893), Richarz (1924), Knopf (1938) and Venkatesh (1952). Bastin (1905) described extremely elongated needles (50:1) which are

probably clinopyroxene, and Tomkeieff (1940) recorded enstatite together with skeletal clinopyroxene in fused sediment.

Aegirine-augite. In one xenolith microlites similar in morphology to the hypersthene exhibited stronger pleochroism and oblique extinction. These were tentatively identified as aegirine-augite. Harker (1904) suspected the presence of aegirine in Torridonian sediment on Soay which was partially fused by a dolerite intrusion.

Magnetite. The glassy matrix of the partially fused sediments is crowded with magnetite dust and with larger magnetite grains. In the buchites the clear glass contains large and small crystals of magnetite, both euhedral and irregular in shape. It is probable that all of the iron ore passed into the liquid phase during fusion (Harker 1904) and in the buchites, at least, all the magnetite present probably recrystallized from the liquid.

4. REACTION BETWEEN PICRITE AND SEDIMENT

Reaction between the picrite and the fused sediment occurred on a microscopic scale in the fused xenoliths and the rheomorphic vein, and on a macroscopic scale in the basal contact zone of Sill 1A. The reaction resulted in: (1) the replacement of olivine crystals by antigorite, (2) the development of mantles of orthopyroxene around olivine crystals, and (3) the isolation of olivine pseudomorphs and picrite inclusions within fused sediment. Hybridization occurred between the picrite inclusions and the fused sediment and isolated olivines are corroded and resorbed by the sediment.

(1) The olivine is usually pseudomorphed by antigorite where it is in contact with the fused sediment, and sometimes the alteration affects olivine crystals within picrite masses enclosed by the sediment, e.g. in the basal contact zone (plates 8C and D). The olivine xenocrysts within fused xenoliths and in the basal contact zone are invariably pseudomorphed, but similar crystals within the rheomorphic vein are usually fresh and unaltered, although a few exhibit marginal alteration. At the junction between a small buchite inclusion and the main picrite above the grit xenoliths of Sill 1A (figure 4) the stages of alteration are preserved. The lower part of the polished specimen shown in plate 8B consists of fused sediment. Above this there is a mixture of quartz grains and olivine pseudomorphs set in a brown glass. A little higher, the brown glass encloses olivine pseudomorphs and plagioclase laths with only a few quartz grains, and abundant prismatic crystals of clinopyroxene are locally developed. The upper part of the specimen consists of normal, coarse-grained picrite. The junction between the

hybrid rock and the unaltered picrite is sharp (seen in thin section), and just below the junction many of the olivine pseudomorphs retain cores of olivine. Some of the olivine crystals straddle the junction, and in these the upper portions are unaltered and the portions below the junctions are altered to antigorite. The sharp boundary between fresh and altered olivine is broken in one place, where the brown glassy matrix extends upwards between the olivine crystals of the picrite. Contact of the matrix with olivine crystals results in marginal serpentinization. Similar effects were observed near the margins of other fused xenoliths. In plate 9C, it can be seen that alteration of the olivine in the picrite surrounding the grit xenoliths has extended further into the picrite than in the example described above.

(2) Mantles of small, weakly pleochroic crystals surround olivine crystals in contact with fused sediment. The prismatic crystals are usually normal and rarely parallel to the olivine pseudomorphs (plate 13). The crystals are too small for 2V to be measured, but they were identified as orthopyroxene by their pleochroism, straight extinction, positive elongation and by their similarity to the hypersthene crystals in the neighbouring glass.

(3) Isolated olivine crystals are dispersed throughout the buchite xenoliths and the rheomorphic vein, and in the basal contact zone they may be highly concentrated (plate 8). They are usually somewhat rounded and corroded (plate 9D). Inclusions of picrite were found only in the rheomorphic vein and in the basal contact zone of Sill 1A. The marginal solution of olivine crystals in the rheomorphic vein is indicated by a concentration of hypersthene microlites in the glass around olivine crystals, and around picrite inclusions. The inclusions have fairly

sharp contacts with the glass and occasionally there is a narrow zone in which the olivines are marginally altered to antigorite. Within these zones, the inclusions consist of normal picrite. Hybridization between the picrite and the fused sediment, therefore, was very slight in the rheomorphic vein, but reaction was more extensive at contacts between xenoliths and the picrite, as illustrated by plates 8B and 9B and C. The nature of the junction between a fused xenolith and the picrite was described above (plate 8B), and it resulted in narrow zones characterized by (a) a mixture of brown glass, olivine pseudomorphs and quartz grains, (b) a few quartz grains, olivine pseudomorphs and plagioclase laths set in an indeterminate brown glassy matrix, with the local development of clinopyroxene crystals. This gave way to (c) normal picrite, with some brown glass extending through the groundmass and producing marginal serpentinization of the olivine. The junction between the picrite and the buchite rims surrounding the grit xenoliths is more abrupt (plates 9B and C), but alteration of the olivines extends further from the junction than in the example described above. Only a few olivine xenocrysts are enclosed by the buchite rims.

In the basal contact zone the fused sediment and the picrite are intimately mixed (plates 8C and D). The glass of the sediment is pale or colourless in parts of the zone, but normally it is brown. A more intense, almost opaque brown matrix, often weakly birefringent, extends through discrete picrite inclusions and olivine crystals in contact with it are altered. The alteration does not always extend throughout the inclusions. The large picrite inclusion shown in plate 8C contains unaltered olivine (and normal picrite) a short distance from its junction with fused sediment. Other picrite inclusions in the basal contact zone

are similar to those found in the rheomorphic vein; i.e. they consist of fresh picrite, with only a narrow border of marginally altered olivine. The nature of the brown matrix made it difficult to distinguish the minerals present in addition to olivine pseudomorphs, but plagioclase laths were detected both within the picrite and in the brown glass surrounding the inclusions. Rare quartz grains were also found within the margins of the discrete inclusions. Quartz grains are abundant in the brown glass enclosing the picrite inclusions, and so are isolated olivine pseudomorphs (plates 8C and D). Differences in colour of the fused sediment as seen in the polished hand specimens appear to be related to the concentration of olivine pseudomorphs, and such concentrations may represent original inclusions which have disintegrated. The olivine pseudomorphs at the edges of the picrite inclusion shown in plate 8D look as if they were drifting away from the inclusion before the liquid was quenched to a glass.

Contacts between the fused sediment and the picrite are thus very variable, and they provide conflicting evidence about the nature of the picrite when hybridization occurred. The sharp junctions characterized by a narrow border of alteration imply that the picrite had crystallized completely by the time it was enclosed by the mobilized sediment, and the discrete nature of many inclusions points to the same conclusion. On the other hand, the presence of so many isolated olivine pseudomorphs in the sediment suggests that consolidation of the picrite was not complete at the time of mixing, and quartz grains could not have penetrated the inclusions unless there was some liquid present within them. Since most of the inclusions appear to have remained fairly rigid, crystallization must have been quite well advanced. However, forcible mixing of fused

sediment with picrite inclusions containing olivine crystals, plagioclase laths and some liquid could result in marginal disintegration of the inclusions (see plate 8D) and the dispersion of olivine crystals through the acid liquid. Mixing of acid and basic liquids is indicated by the brown colouration of the glass in the fused sediment of the basal contact zone. Liquid and quartz grains from the fused sediment could have penetrated the inclusions, and quenching of the mixed liquid would have trapped quartz grains and volatiles within the discrete inclusions.

Reaction would be expected to occur between the fused sediment and the picrite whenever sufficient liquid developed in the sediment for it to become mobile, and the variety of reaction phenomena exhibited suggests that this did not always occur at the same stage of consolidation of the picrite. In most instances it occurred when the picrite consisted largely or completely of crystals. This indicates a time lag between the intrusion of the picrite and the development of liquid within the sediment. A xenolith completely enclosed by the sill would be expected to reach the temperature of the enclosing picrite, but consideration of the cooling rate of the picrite and the heating rate of a xenolith confirms that the maximum temperature reached by the xenolith must be less than the temperature of the picrite when it was intruded. The development of large amounts of liquid within a xenolith would depend not only upon the temperature of the xenolith and the volatile ingredients it contained but also upon the diffusion of volatiles from the picrite. Concentration of volatiles within the xenolith would not occur instantaneously and there would be a distinct time lag between the conduction of heat to the xenolith and the development of liquid within it. Figure 12 illustrates diagrammatically the cooling and heating curves of the

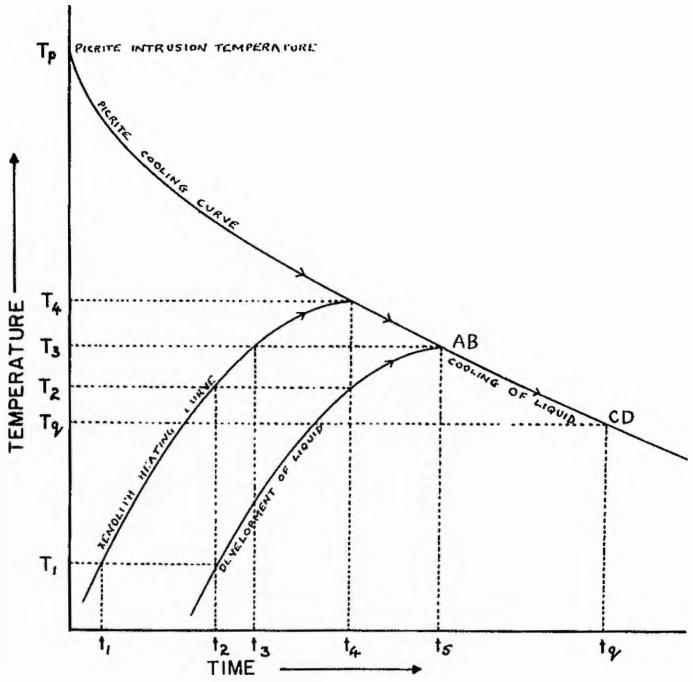


Figure 12. Diagrammatic representation of the cooling curves and heating curves of the picrite magma and a xenolith, respectively. The third curve represents the stage at which an "equilibrium" liquid develops within the xenolith, and the horizontal lines between this curve and the heating curve represent the time lag between the attainment of a given temperature and the development of a liquid which can exist in equilibrium at this temperature.

picrite and a xenolith, respectively, and the time lag between the heating curve for the xenolith and the development of liquid within it is represented by the space between the heating curve and the curve showing the development of liquid.

If the temperature of a xenolith were maintained at the temperature T_1, reached after a time t_1, the equilibrium liquid for this temperature would develop at a later time, t_2. However, after a time t_2, the temperature of the xenolith would have increased to T_2. The equilibrium

liquid for this temperature would develop at a time t_4, but by this time the temperature of the xenolith (and the liquid it contains) would have reached the temperature of the cooling picrite, T_4. By the time t_5, both picrite and xenolith would have cooled to the temperature T_3, and the composition of the liquid developed within the xenolith would correspond to that liquid which would have developed if the xenolith had been maintained at the temperature T_3 throughout the time interval t_3 to t_5. After the time t_5, the picrite and the liquid would cool together, with crystallization of minerals from the liquid developed by fusion, and the liquid would be quenched to a glass after a time t_q when the temperature reached T_q.

The intrusion temperature of the picrite, T_p, was therefore greater than the maximum temperature reached by the xenolith, T_4. Although the liquid in the xenolith would also reach the temperature T_4, the composition of the liquid developed would not represent the equilibrium state at this temperature. Not until the temperature had fallen to T_3 could the composition of the liquid correspond to an equilibrium liquidus temperature. The difference between T_p and T_4 will depend upon the rates of cooling and heating of the picrite and xenolith respectively. The initial cooling rate of the picrite would be greater for higher temperatures of intrusion, and a higher intrusion temperature would probably result in a greater temperature interval between T_p-T_4. The interval would also be greater for sediments further away from the picrite, because the heating rate for such sediments would be slower. The temperature interval T_4-T_3 will depend upon the time lag between the heating curve and the development of the "equilibrium" liquid within the xenolith. The high viscosity of liquids of granitic composition

is well known (Schairer 1950), and without the action of volatile components a rock of granitic composition would have to be maintained above its fusion temperature for a very long time before an equilibrium assemblage of liquid and crystals would develop. The magnitude of the temperature interval T_4-T_3 will therefore depend mainly upon the rate of diffusion of volatiles from the picrite, which will depend in turn upon the amount of volatiles present in the picrite and the ease with which they could enter the sediment. The temperature interval would clearly be greater for sediments further away from the sill than for those in contact with the picrite, but with so many, unknown, variable factors it is impossible to estimate the magnitude of the interval T_p-T_3.

Walker and Poldervaart (1949) investigated in detail the transfusion and melting of sediments by the Karroo dolerites and the injection of rheomorphic veins. They concluded from petrographic evidence that the maximum activity of partially fused sediments, which would probably correspond to the maximum development of liquid in the sediments, occurred at temperatures well below 1000°C after the solidification of most of the dolerite. On the basis of other evidence they estimated that the dolerites were intruded at temperatures between 1100°C and 1150°C. The maximum development of liquid therefore occurred more than 100°C to 150°C below the dolerite intrusion temperature. Sills 1 and 1A are small intrusions and the texture of the picrite suggests that they cooled more rapidly than most of the larger Karroo dolerite intrusions. By analogy with the evidence presented by Walker and Poldervaart it is probable that the temperature of maximum development of liquid in the xenoliths and fused sediments was more than 150°C below the intrusion

temperature of the picrite, i.e. the temperature interval T_p-T_3 was greater than 150°C.

It is probable that before hybridization between the picrite and fused sediment occurred, the picrite had cooled through at least 150°C. It is not surprising, therefore, that the picrite forms rigid blocks within the fused sediment, because almost complete crystallization of the picrite would be expected in such a large temperature interval. If the last liquid in the picrite crystallized at the temperature T_3 (figure 12), the fused sediments in contact with the picrite during the time t_4 to t_5 would have reacted with picrite containing some residual liquid, and the fused sediments in contact with the picrite during the time interval t_5 to t_q would have reacted with crystallized picrite. In order to account for the diversity of observed reaction phenomena, it must be concluded that the temperature of final crystallization of the picrite was near to the temperature of maximum activity of the sediments.

The complex nature of the basal contact zone of Sill 1A and the injection of a rheomorphic vein suggest that the region was subject to stresses. A similar conclusion was reached in order to explain the translation lamellae and undulose extinction occurring in some olivine crystals and the presence of fine-grained offshoots from Sill 1. The fact that the rheomorphic vein contains inclusions of normal, crystallized picrite, suggests further that the stresses were recurrent, occurring before and after the final consolidation of the picrite.

5. THE ROLE OF VOLATILES

In the Introduction (section 1), it was suggested that the fusion of sedimentary xenoliths enclosed by basic and ultrabasic magmas may be more dependent upon special conditions, especially the amount and nature of the volatile ingredients in the sediment and magma, than upon the temperature of the magma. There are conflicting views about the proportion of volatiles contained by ultrabasic magmas. For instance, Vogt (1922) believed that peridotites and dunites were dry magmas, whereas Hess (1938) believed that peridotite magmas of the orogenic regions were highly aqueous. There is evidence that the widespread fusion of sediments below Sill 1A was caused predominantly by volatiles released from the picrite (section 3.1), although the picrite itself provides little evidence that volatiles were present when the magma was emplaced. The olivine is remarkably fresh except in the chilled margins and where it is in contact with fused sediment. Water in the fused sediment was undoubtedly responsible for the alteration of nearby olivines, and it is possible that serpentinization of olivines near the margins of the sills was effected by original water trapped in the rapidly chilled magma.

Fusion of the sediment was initiated by the release of fluxes resulting from the decomposition of sericite. Volatile ingredients from the magma (particularly H_2O and P_2O_5) were subsequently concentrated in the interstitial melt, enhancing its fluxing power and facilitating the development of large quantities of liquid. The degree of fusion varies even near Sill 1A suggesting that the volatiles in the picrite magma became concentrated in favorable localities after intrusion. It is possible that the development of an initial melt was necessary for the later concentration of volatiles from the picrite. Decomposition

of sericite near Sill 1A may have provided avenues of escape for the volatiles in the picrite magma by forming passageways between the grains of the sediment. Concentration of volatiles in Sill 1A is indicated by the coarser texture of the feldspar and pyroxene compared to that in Sill 1, and the coarseness of the texture within sill 1A appears to increase towards the basal contact zone (plates 4 to 6). No evidence of metamorphism was found in two specimens collected from the dolerite dyke intersected by Sill 1 (figure 3) and fusion of sediments by other picritic intrusions of the group is, on the whole, rare (Drever and Johnston 1958). Muscovite is not a common constituent of the Beinn Brheac sediments (section 2.1) and it would be interesting to see if fusion occurred only in mica-bearing sediments.

The flux initially developed in the sediment was strongly reducing as shown by the reduction of hematite to magnetite (Part III), but the fused xenolith in Sill 1 has a ratio of ferric to ferrous iron greater than 1 (table 10). The partial pressure of oxygen in water increases with the partial pressure of water and with temperature (Kennedy 1948), and the increase in temperature and in the amount of water dissolved in the melt as fusion progressed must have been sufficient to reverse the strongly reducing conditions prevalent at lower temperatures. Larsen and Switzer (1939) found that oxidation occurred during fusion of a tonalite xenolith enclosed by olivine basalt.

Most of the volatiles must have escaped from the picrite, with the exception of those trapped in the chilled margins, otherwise the olivine in the picrite would have been altered to serpentine. In their study of the system MgO-SiO_2-H_2O Bowen and Tuttle (1949) proved that only below 430°C at a water vapour pressure of 15,000 psi does forsterite

decompose to serpentine and brucite. Serpentinization of olivine must therefore have occurred at a low temperature when movement and hybridization of picrite and fused sediment had ceased. The virtual absence of serpentinization in the olivines and picrite inclusions in the rheomorphic vein indicates that diffusion of water from the glass at low temperatures was not effective, and the extent of serpentinization in the basal contact zone and at junctions between xenoliths and picrite may therefore be regarded as a measure of the extent of hybridization which occurred at higher temperatures.

PLATES 8 TO 13

Plate 8.

A. Partially vitrified sediment below the basal contact zone of Sill 1A. The dark, fine-grained sediment has apparently been intruded into the coarser grained sediment. Scale: x3/4

B. Specimen 75, Sill 1A. The contact between a fine-grained glassy xenolith (below) and the fresh picrite (above). The reaction zone is characterized by a brown glassy matrix enclosing olivine pseudomorphs (black). Some greatly elongated olivine crystals are visible. Scale: x1.

C and D. Specimens from the basal contact zone of Sill 1A. The light and dark grey areas represent fused sediment containing isolated olivine pseudomorphs (black). Picrite occurs as discrete inclusions but the concentration of isolated olivine crystals in the glassy matrix shows that other inclusions have disintegrated and become dispersed. Scale: C, x3/4; D, x1.

Plate 9.

A. Fused xenolith, specimen 129, Sill 1. The specimen consists largely of glass containing resorbed quartz grains (white spots). The white patch at the bottom left was not examined in thin section. Scale: x3/4.

B and C. Sections cut through a grit xenolith to show the variation in width of the fine-grained buchite rims separating the grit from the picrite. The grit contains quartz, feldspar, and quartzite pebbles, of varying sizes. The picrite (top) contains pseudomorphs of olivine (black), and a few olivine xenocrysts are isolated in the buchite rim. Scale: x3/4.

D. The basal contact zone of Sill 1A. The dark background containing corroded olivine crystals is fused sediment, contaminated by igneous material. The olivine crystals are marginally altered to serpentine (olivine crystals enclosed by fused sediment in the basal contact zone are usually completely pseudomorphed). The brown glassy matrix grades into the picrite inclusions whose edges are shown by a fine mesh of plagioclase crystals. Note the variety of shapes and sizes of olivine crystals. Scale: x10.

Plate 10.

A and B. Feldspar crystal in a grit xenolith (Sill 1A) showing the development of glass along the cleavages. In plain light, (A), the crystal appears to merge into the glassy matrix. Scale: x200.

C and D. Feldspar crystal from the same specimen as plates 10A and B. The feldspar, barely distinguishable from the glassy matrix in plain light, has separated into several fragments which retain optical continuity. Below the feldspar there is a corroded quartz grain. Scale: x200.

Plate 11.

Cordierite crystals from the fused xenolith (specimen 129) in Sill 1; six sided prisms containing inclusions of ore. Scale: x400.

A. Six sided prisms seen in cross section. The light background is glass. At the bottom right is a more complicated crystal, probably a section across a parallel growth of cordierite.

B. The same as plate 11A, with nicols crossed and a one wave length retardation plate inserted. The lighter band across the centre of the largest cordierite crystal represents two twinned sectors.

C. The large crystal in the glass is probably a section across a parallel growth of cordierite. Next to it there is a complete six-sided prism, contained within the thickness of the section.

D. A cruciform twin of cordierite, combined with parallel growth. The crystal is bordered by cracks in the surrounding glass.

E. Plate 11D with nicols crossed.

F. Plate 11E with the one wave length retardation plate inserted to show the twin units and the composition planes.

Plate 12.

Scale: x200.

A and B. The fused xenolith from Sill 1, specimen 129. Colourless glass containing accicular hypersthene and rounded quartz grains surrounded by fringes of inverted tridymite.

C and D. Fused xenolith from Sill 1A. Green tinted glass containing accicular hypersthene and resorbed quartz grains surrounded by secondary quartz rims. The elongated hypersthene crystal at the left centre of plate 12C is skeletal. The stouter crystals may be aegirine-augite.

Plate 13.

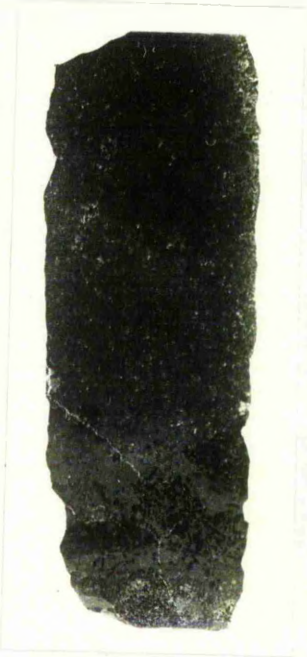
Olivine crystals isolated in colourless glass. Scale: x200.

A and B. Fused xenolith, specimen 129. Small hypersthene crystals border the olivine xenocryst, and skeletal hypersthene occurs in the glass. Skeletal growth of cordierite crystals is illustrated by the short extensions to their prismatic faces (B).

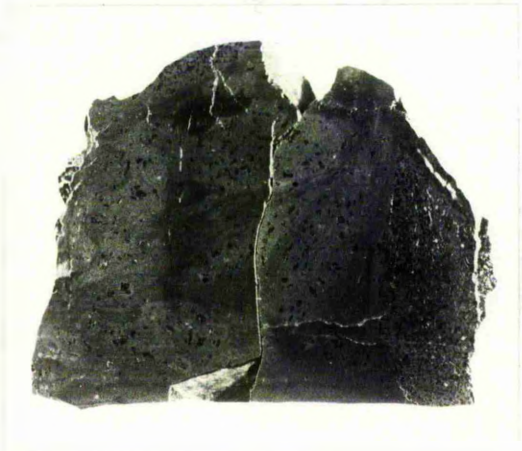
C and D. The rheomorphic vein. Hypersthene crystals are concentrated around the olivine crystal, and are plentiful in the colourless glass. The quartz grain is surrounded by a secondary quartz rim (D).

PLATE 8.

A.



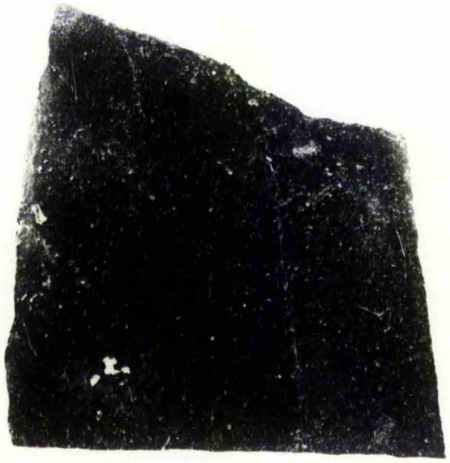
B.



C.

D.

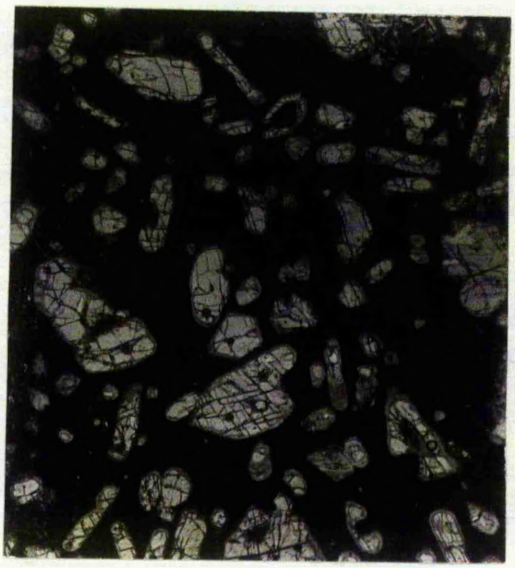
PLATE 9.



A.

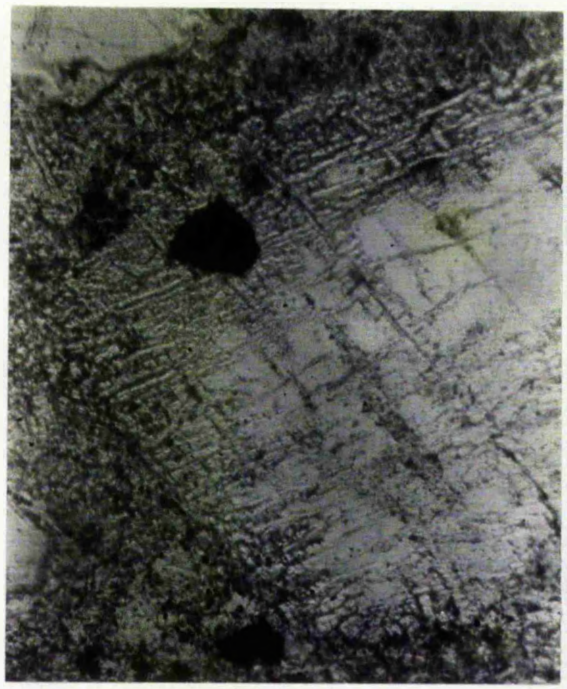
B.

C.

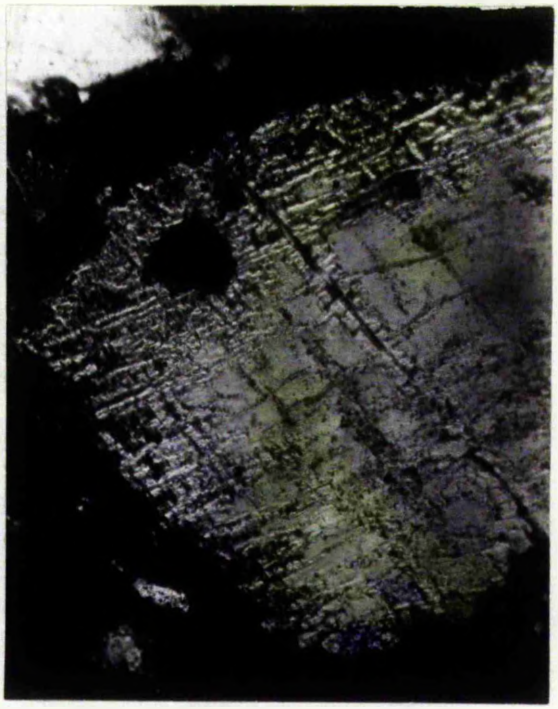


D.

PLATE 10.



A.



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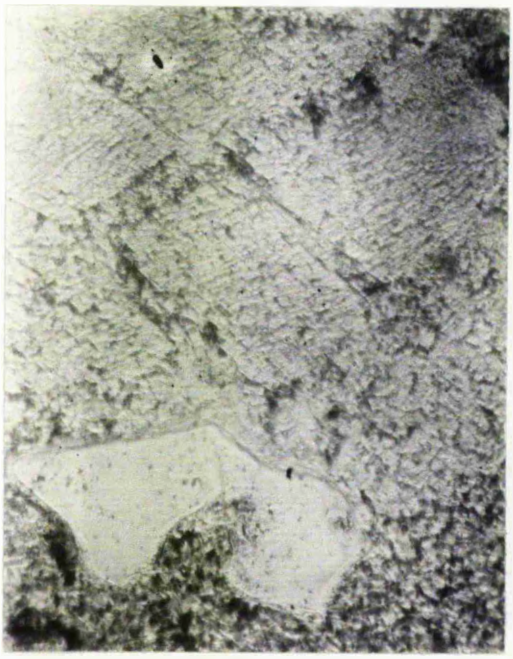
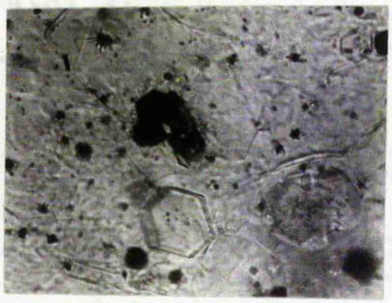


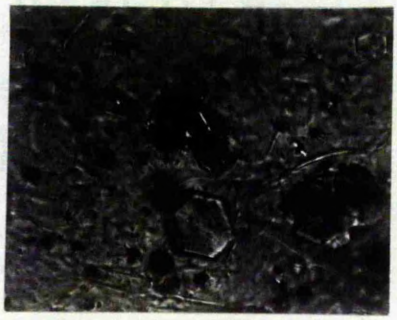
C.

D.

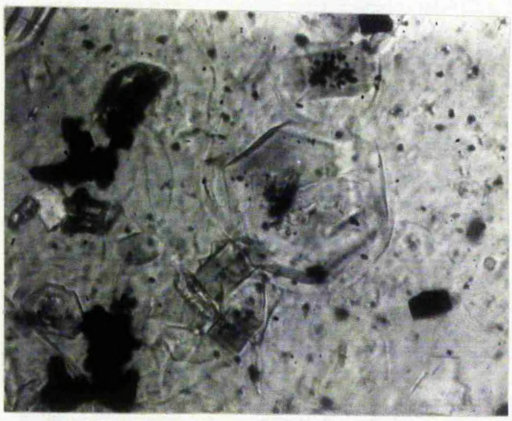
PLATE 11.



A.



B.



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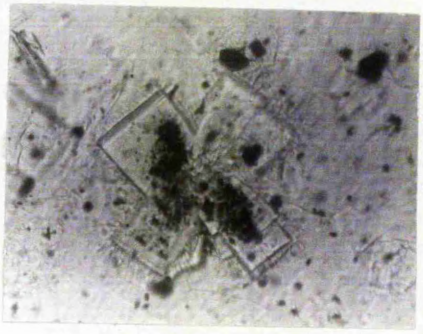

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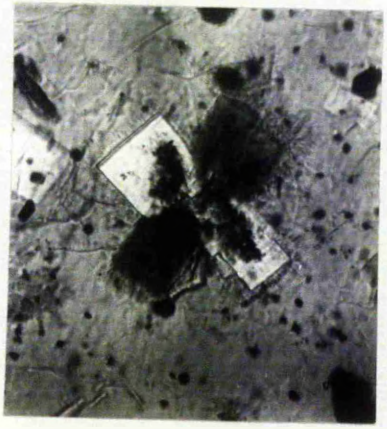
E.



F.

PLATE 12.

A.

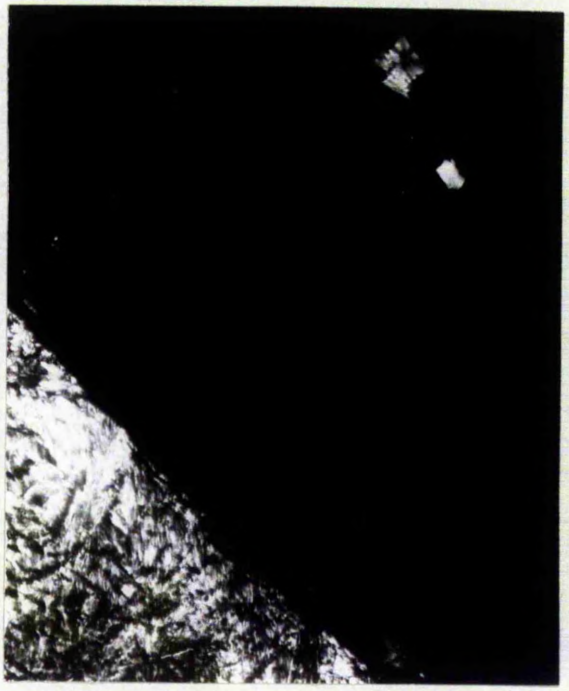
B.

C.

D.

PLATE 13.

A.



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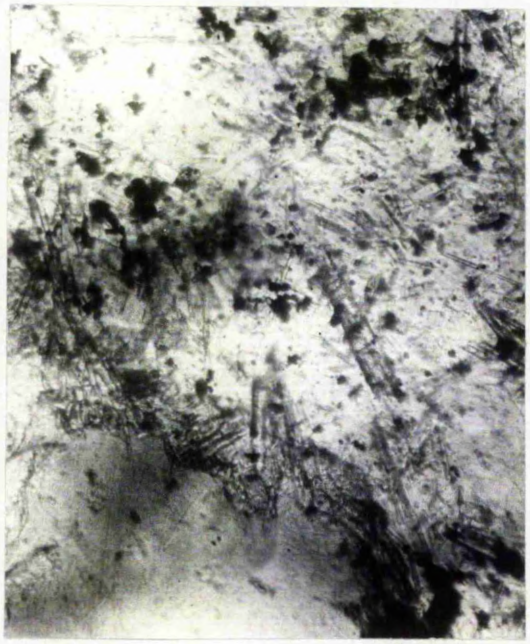
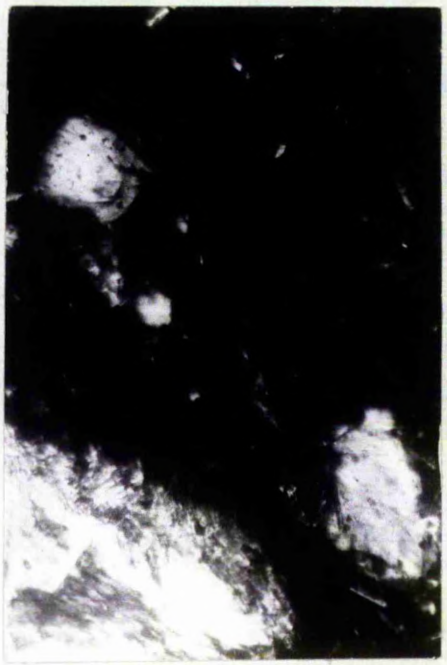


C.



D.

PART III

EXPERIMENTAL EVIDENCE FROM PHASE EQUILIBRIUM STUDIES

1. EXPERIMENTAL EVIDENCE RELATED TO THE MELTING TEMPERATURES OF PICRITIC ROCKS

1.1. Introduction

Bowen has frequently commented upon the high temperatures required for the intrusion of ultrabasic liquid magmas and upon the lack of evidence for high temperatures in the contact relations of ultrabasic rocks (e.g. Bowen and Tuttle 1949). Sill 1 is exceptional in this respect but even here the field evidence does not support the hypothesis of Vogt (1921) that dunites and peridotites were emplaced as very hot liquid magmas with temperatures near 1600°C. Vogt suggested that the addition of fayalite to forsterite (m.p. 1890°C) would produce marked lowering of liquidus temperatures, but subsequent experimental work in the system MgO-FeO-SiO_2 (Bowen and Schairer 1935) proved that a temperature of 1800°C was required for the complete liquefaction of olivine up to $Fo_{80}Fa_{20}$ in composition. Osborn and Tait (1952) studied the system diopside-anorthite-forsterite and found that, although some liquid developed at rather low temperatures (1270°C) for mixtures rich in forsterite, the amount of liquid remained small until very high temperatures were reached. Harker (1909) considered that many ultrabasic rocks were emplaced as liquid magmas and he believed that the addition of volatile components would aid the liquefaction of accumulated olivine crystals at moderate temperatures (oral communication to Bowen 1928, p. 166). Both Harker and Bowen realised the difficulty of visualizing a process whereby volatiles could be added to a largely crystalline mass. The lowering of liquidus temperatures which might be produced by the action of volatile materials under pressure is shown by Yoder's (1954) results in the system diopside-anorthite-water. Under a pressure of 5,000 bars

of water vapour, the melting point of anorthite is lowered by about 320°C, and the eutectic temperature by about 180°C. These results are preliminaries to the study of the system diopside-anorthite-forsterite-water, in which the compositions of many ultrabasic rocks could be closely approximated.

In order to explain certain field relationships of peridotites in orogenic zones Hess (1938) postulated that these rocks were emplaced, at low temperatures, as highly aqueous ultrabasic liquids derived by differential fusion of the ultrabasic substratum. Investigation of the system MgO-SiO_2-H_2O (Bowen and Tuttle 1949) does not support this hypothesis. No liquid phase occurred at temperatures up to 1000°C and pressures up to 30,000 psi. Liquidus determinations were not possible with the available apparatus, and the effect of water vapour under pressure on the melting relations of ultrabasic compositions remains uncertain. For the peridotites of the orogenic zones, where evidence of high temperatures is absent, the most satisfactory hypothesis in view of the available experimental data is that of intrusion of a largely crystalline peridotite magma. Hess (1955), however, points out the difficulties inherent in this mechanism of intrusion and believes that the field evidence for the magmatic origin of these rocks should take precedence over the experimental evidence.

There is convincing evidence that some of the ultrabasic minor intrusions of the Skye group were emplaced at high temperatures. The peridotites were hotter than the gabbros, according to Harker (1904, 1909), and there is no doubt concerning the high temperature of Sills 1 and 1A when they were intruded (section 2.3). The estimated temperature of intrusion, although high, is nevertheless much lower than the

very high temperatures demanded by the experimental work described above. However, Ricker (1952) discovered that the addition to forsterite of calcium orthosilicate as well as fayalite does produce considerable lowering of these high liquidus temperatures.

1.2. The Quaternary System $CaO-MgO-FeO-SiO_2$ and Related Systems

Ricker (1952) determined the phase relationships for some joins in the quaternary system $CaO-MgO-FeO-SiO_2$ and Osborn (1954) discussed the importance of the system in relation to steel plant refractories. This system is important also in relation to ultrabasic igneous rocks. For instance, the oxides CaO, MgO, FeO and SiO_2 constitute 86.9 per cent of the analyzed picrite (table 7). The oxides Al_2O_3 and Fe_2O_3 make this total up to more than 97 per cent of the rock. A knowledge of the phase relationships in the systems involving these six oxides is thus of fundamental importance to the genesis of picrites, and such systems are being studied with particular reference to steel plant refractories and slags (Osborn 1954). The compositions of interest to the steel industry do not always coincide with those of interest to petrologists, but the parts of the system $CaO-MgO-FeO-SiO_2$ studied in most detail by Ricker (1952) are closely related to picritic compositions. Information concerning the effect of Al_2O_3, in addition to these four components, is available from the related system $CaO-MgO-Al_2O_3-SiO_2$ (Osborn *et alia* 1954), but it is more difficult to estimate the effect of Fe_2O_3. The proportion of Fe_2O_3 present in an iron bearing melt depends upon its composition, its temperature and the partial pressure of oxygen in the atmosphere. The oxidation state of iron is not normally considered in petrogenetic discussions, the usual practice being to recalculate all iron as FeO or

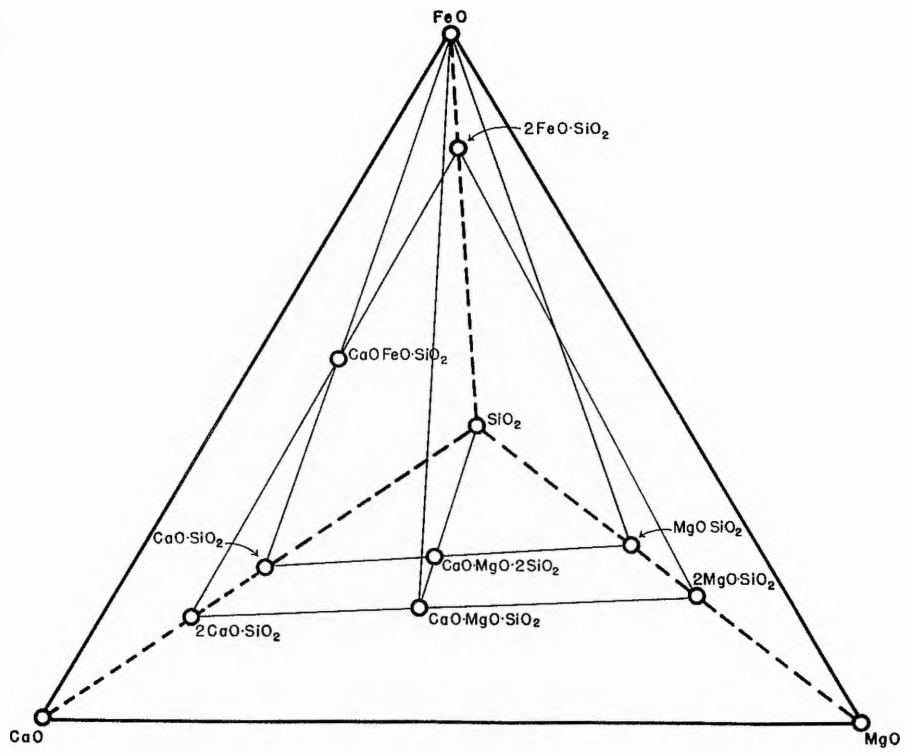
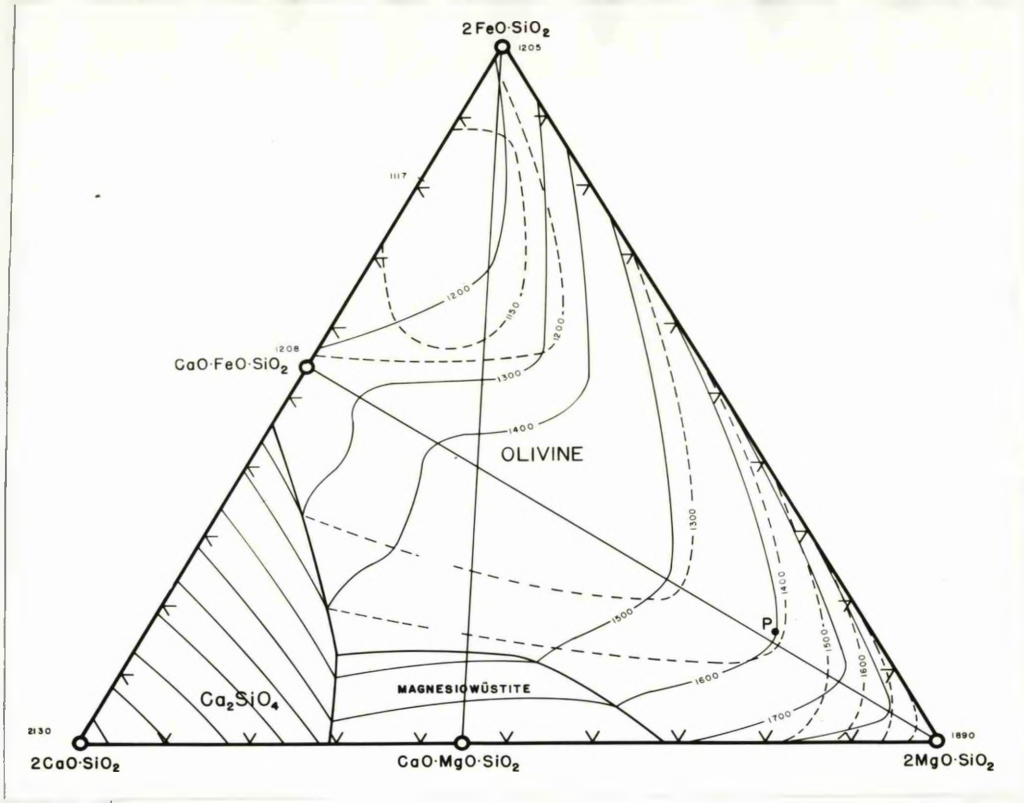
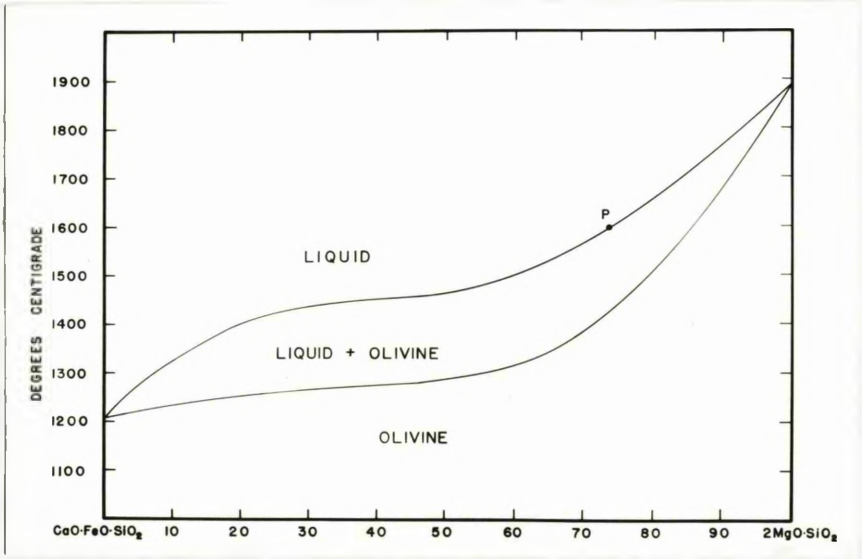


Figure 13. Tetrahedron representing the quaternary system CaO-MgO-FeO-SiO_2. Lighter lines bound the triangular joins discussed in the text, and the compounds mentioned are plotted in weight per cent in terms of the four components (after Richer 1952).

as Fe_2O_3 and to consider it as such. However, the effect of changes in the oxidation state of iron in slags and refractories is considerable (Osborn 1954, 1956), and it may be expected that different oxidation states in magmas (as indicated by the ratio of ferric to ferrous iron in analyzed rocks) may have a considerable effect upon their temperatures and crystallization histories (cf. Kennedy 1948). Extension of controlled atmosphere studies of iron-bearing systems (for example, MgO-FeO-Fe_2O_3-SiO_2, Muan and Osborn 1956) will certainly prove useful



A.



B.

Figure 14. A. Equilibrium diagram for the olivine join in the quaternary system CaO-MgO-FeO-SiO_2. Heavy lines are boundary curves. Light lines are liquidus isotherms. Light dashed lines are solidus isotherms in the olivine field.
B. Liquidus and solidus curves along the join $2MgO.SiO_2$-CaO.$FeO.SiO_2$. This section is not a binary system.
P is the point representing the composition of the analyzed picrite (table 7); all MgO, FeO and CaO was calculated as normative orthosilicate and recalculated to 100 per cent.
Both diagrams after Ricker (1952).

to petrologists concerned with the origin of ultrabasic and basic igneous rocks.

The phase relations in a quaternary system may be represented by a tetrahedron whose four corners represent the four components. Figure 13 shows a tetrahedron for the system CaO-MgO-FeO-SiO_2; only the positions of compounds and joins referred to in the following discussion are shown in the diagram. For ultrabasic rocks, rich in olivine, the orthosilicate join of this system is of fundamental importance. The general phase relationships for the join were determined by Ricker (1952); primary crystallization fields and isotherms for the liquidus surface are reproduced in figure 14A. Tie lines for coexisting liquids and olivines were not determined but the position of the solidus was located in parts of the system and sketched approximately elsewhere (dotted lines in figure 14A). Three primary phase fields appear on the join, but the field of olivine occupies most of the area. There is a temperature valley on both liquidus and solidus surfaces of the olivine field, extending initially from $2MgO.SiO_2$ (forsterite) towards $CaO.FeO.SiO_2$. In the central part of the diagram the valley opens out into a plateau of considerable extent and, from this plateau, the valley continues towards the temperature minimum on the join $CaO.FeO.SiO_2$-$2FeO.SiO_2$. The marked lowering of liquidus temperatures produced by the addition of $CaO.FeO.SiO_2$ to $2MgO.SiO_2$ is well illustrated by the section across the olivine join shown in figure 14B. In this section, compositions containing almost 60 weight per cent of forsterite are completely liquid at 1500°C. The effect of adding CaO and Al_2O_3 to forsterite is not so marked. In the system diopside-anorthite-forsterite (Osborn and Tait 1952), compositions containing 60 weight per cent of forsterite are completely liquid only

above 1600°C, and in the binary system $2MgO.SiO_2$-$2FeO.SiO_2$. a temperature of about 1730°C would be required to liquefy a composition containing 60 weight per cent of forsterite (figure 14A). The temperature differences in these systems are therefore very large and, since ultrabasic rocks (dunites excepted) contain appreciable amounts of CaO and FeO, it seems possible from this evidence that ultrabasic rocks could exist as liquid magmas at temperatures lower than previously suspected from experimental data. The addition of other components which exist in the natural rocks (including volatiles) would almost certainly lower even further the temperature at which the rocks could exist as liquid magmas.

The field and petrographic study of Sill 1 and 1A favors the hypothesis that the picrite was intruded as a hot liquid (see Part IV). For this reason, preliminary experiments were carried out on crushed samples of the analyzed picrite from Sill 1A in an attempt to determine its melting interval at varying pressures of water vapour, and of water vapour plus hydrogen fluoride. Because the four components CaO, MgO, FeO and SiO_2 constitute 86.9 per cent of the picrite, the system picrite-water is closely related to the quaternary system. The simple silicate systems, which can be treated theoretically in terms of the phase rule, establish patterns of behaviour which must be considered in the development of any petrological hypothesis, but the study of natural samples in the presence of one or more volatile components under pressure approximates more closely to the conditions of formation of the rocks. Although the results of such empirical observations cannot be treated theoretically, they might serve as a useful check on conclusions reached from petrographic studies. In the melting experiments, no attempt was

made to control the oxidation state of the iron in the picrite, a factor which may affect the phase relations and liquidus temperatures considerably (Osborn 1954, 1956). Interpretation of the results was made difficult by the persistent occurrence of dendritic crystals of olivine, and larger quench phases (probably olivine) in the quenched liquid. The temperature of the beginning of melting was lowered by the presence of water vapour under pressure, and the addition of small amounts of hydrogen fluoride produced further lowering. The temperature of complete liquefaction would undoubtedly be similarly lowered, but liquidus determinations were not obtained. From the preliminary results, 15,000 psi of water vapour would lower the beginning of melting temperature of the picrite by about 200°C. The complete determination of the melting relations of a natural picrite in the presence of volatile materials would be a major research problem, but the writer hopes to continue with this study in the near future.

An estimate of the temperature at which the analyzed picrite would be completely liquid at atmospheric pressure, without volatile components, may be obtained from the liquidus temperatures sketched by Ricker (1952). The composition of the picrite (P) has been projected on to the orthosilicate join of the quarternary system in figure 14A. All the MgO, FeO and CaO were calculated as orthosilicates and the percentages of the normative orthosilicates were recalculated to 100 per cent. The recalculated percentages give the projected position of the picrite on the olivine join. The projected analysis lies almost at the intersection of the 1600°C liquidus isotherm and the join $2MgO.SiO_2$-$CaO.FeO.SiO_2$. The effect on liquidus temperatures of oxides in excess of the orthosilicate ratio can be approximately estimated. The normative

orthosilicates constitute 75.1 weight per cent of the picrite, and the remaining oxides are: SiO_2, 11.8 per cent; Al_2O_3, 8.82 per cent; Fe_2O_3, 1.46 per cent; $H_2O(+)$, 1.62 per cent; alkalis and minor constituents 1.03 per cent. Because of the excess silica, the picrite must be represented within the quarternary tetrahedron by a point lying between the orthosilicate join and the SiO_2 corner of the tetrahedron. Its displacement from the olivine join can be represented in projection on the join $CaO.MgO.SiO_2$-FeO-SiO_2. This join is approximately perpendicular to the olivine join, which intersects it in the line $CaO.MgO.SiO_2$-$2FeO.SiO_2$. The point P in figure 22 is the projection of the point from within the tetrahedron on to this join. Projection of the analysis on to the two joins (shown in figures 21 and 22) fixes quite closely the position of the analyzed picrite within the quaternary tetrahedron (see figure 13). The excess silica thus places the picrite just over two thirds of the way between the orthosilicate join and the join $MgO.SiO_2$-$CaO.SiO_2$-FeO. Ricker (1952) was able to sketch the isotherms for the liquidus surface on the later join and the picrite was projected also on to this surface. Near the projected point, the liquidus surface slopes gently and a good estimate of the liquidus temperature could not be obtained. The temperature is between 1520°C and 1540°C. Assuming a regular change in liquidus temperature from this point to the corresponding point on the olivine join, the composition represented by the point within the tetrahedron would probably be completely liquid at a temperature near 1560°C.

The additional effect on liquidus temperatures of the Al_2O_3 in the picrite can be estimated from the data obtained by Osborn *et alia* (1954) for the quaternary system CaO-MgO-Al_2O_3-SiO_2. They present diagrams

showing liquidus temperatures for a series of planes of constant Al_2O_3 content within the quaternary tetrahedron. The planes are designated the "5 per cent Al_2O_3 plane", the "10 per cent Al_2O_3 plane", etc. If the CaO, MgO, SiO_2 and Al_2O_3 of the analyzed picrite are recalculated to 100 per cent, the Al_2O_3 amounts to 10.1 per cent. The position of the picrite, represented by a point within the quaternary tetrahedron, therefore lies almost on the 10 per cent Al_2O_3 plane. The percentages of CaO, MgO and SiO_2 in the picrite were recalculated to 100 per cent and to 90 per cent, and the corresponding points were plotted on the planes CaO-MgO-SiO_2 (one side of the tetrahedron), and on the 10 per cent Al_2O_3 plane, which is, of course, parallel to the CaO-MgO-SiO_2 plane. According to Osborn *et alia* (1954) the liquidus temperatures for the compositions plotted on the two planes are 1650°C and 1600°C respectively. The effect of adding 8 per cent of Al_2O_3 to a mixture of CaO, MgO and SiO_2 in the ratios corresponding to the analyzed picrite is to lower the liquidus temperature by 50°C. Insufficient information is available for the systems MgO-FeO-Al_2O_3-SiO_2 and CaO-FeO-Al_2O_3-SiO_2 to apply the same method to them, but when more results are obtained application of the same method to these systems would permit a closer estimate of the effect of Al_2O_3 on the liquidus temperature. The addition of the appropriate percentage of Al_2O_3 to the composition P within the tetrahedron representing the system CaO-MgO-FeO-SiO_2 would probably reduce the liquidus temperature to about 1510°C.

The effect of Fe_2O_3 on the picrite is less readily estimated. With the experimental technique used by Ricker (1952), all the charges contained a small amount of ferric iron (amounting to 1 or 2 per cent near the composition P) which was treated as FeO. This is about the same amount

as contained in the picrite. Reasons have been given for not treating all the iron in igneous rocks as FeO, but for the purpose of estimating the effect of Fe_2O_3 on the liquidus temperatures CaO, MgO, and the total Fe calculated as FeO, were calculated as normative orthosilicates, and recalculated to 100 per cent. This procedure resulted in a slight shift of the projected point P towards $2FeO.SiO_2$ in figure 14A. The new point (corresponding more closely in composition one of Ricker's (1952) charges) lies on the liquidus surface at a temperature about $10^{o}C$ lower than the point P. It may be tentatively concluded that the addition of 1.46 per cent of Fe_2O_3 to the composition containing the oxides CaO, MgO, FeO, SiO_2, and Al_2O_3 in the same ratios as in the picrite, would lower the liquidus temperature of the mixture by $10^{o}C$, reducing it to $1500^{o}C$. The effect of the 1.03 per cent of alkalis and minor constituents in the picrite, although probably slight, would undoubtedly lower the liquidus temperature. The estimated temperature at which the picrite would be completely liquid is therefore less than $1500^{o}C$. The effect of dissolved volatiles under pressure, as discussed above, would lower this temperature even further.

1.3. Petrological Speculation

The discovery of a plateau on the liquidus surface of the orthosilicate join in the quaternary system $CaO-MgO-FeO-SiO_2$ (figure 14A) provides qualitative information about three petrological processes. The phase relations are admittedly tentative in many parts of the tetrahedron, and the petrological deductions are therefore speculative. As further information becomes available for this quaternary system and the related systems containing Al_2O_3, firmer petrological inferences may be

drawn from them. The section across the olivine join, illustrated in figure 14B, is not a binary system, because tie lines connecting liquids and crystals in equilibrium do not lie in the plane of the section. However, the tie lines connecting co-existing liquid and olivine cannot be far removed from the plane of the section. The compositions of picritic rocks (projected on to the orthosilicate join in figure 21) lie close to the section, and the average composition of the olivine crystals in these rocks is $Fo_{90}Fa_{10}$ (Drever and Johnston 1958). Tie lines connecting the projected rocks and the olivine crystals in them intersect the join $CaO.FeO.SiO_2$-$2MgO.SiO_2$ at angles of about 10^{o}. It seems probable that the tie lines for compositions in the olivine join also intersect the section (figure 14B) in quite small angles and, for the purposes of discussion, it may be assumed that the section is a binary system at least between the temperatures $1600^{o}C$ and $1400^{o}C$. The plateau on the liquidus surface of the olivine join exists in this temperature interval.

With cooling, the composition of a liquid on the plateau would change considerably, while the composition of the crystallizing olivine would change only slightly. For example, the composition of the liquid would change from 58 per cent forsterite at $1500^{o}C$ to 19 per cent forsterite at $1400^{o}C$, while the composition of the olivine crystallizing from this liquid would change only from 79 per cent forsterite to 71.5 per cent forsterite. Moreover, in this temperature interval of $100^{o}C$, more than half of the liquid would crystallize. Similarly, starting at $1400^{o}C$ with a mixture of about 50 per cent liquid (of composition forsterite 19 per cent) and 50 per cent of olivine crystals (of mean composition about 75 per cent forsterite) an increase in temperature of only $100^{o}C$

would be sufficient to dissolve all the olivine. Although the section is not a binary system, the persistence of the plateau over the central part of the olivine join indicates that the general relations described above are valid. Extension of these relationships to rocks is less certain, because the basalts projected on to the olivine plane are quite far displaced from the olivine join within the tetrahedron (see figure 22). They may be extended to peridotites and picritic rocks, however, because the plateau feature persists on liquidus surfaces near the metasilicate join. Ricker (1952) sketched the liquidus surface for the join $CaO.SiO_2$-$MgO.SiO_2$-FeO. On this join, the temperature falls very slowly from $MgO.SiO_2$ towards $CaO.FeO.SiO_2$, with a somewhat steeper gradient for compositions near 50 per cent $MgO.SiO_2$. Temperatures over the central and magnesian rich portions of the liquidus are lower than over corresponding areas on the orthosilicate join, and the temperature variation over the whole surface is less than that over the orthosilicate surface. Fairly level areas persist also on liquidus surfaces in the system CaO-MgO-SiO_2, and on the 5 per cent, the 10 per cent and the 15 per cent Al_2O_3 planes of the system CaO-MgO-Al_2O_3-SiO_2 (Osborn *et alia* 1954). The level areas extend from the forsterite field across the field of pyroxene, with liquidus temperatures between 1400°C and 1300°C, and on the 15 per cent Al_2O_3 plane, the level area extends across the primary fields of pyroxene and anorthite. The plateau feature thus appears to persist in systems containing CaO, MgO, FeO, Al_2O_3, and SiO_2, and for compositions moving away from the ultrabasic compositions rich in forsterite the temperatures on the level liquidus areas decrease slowly as the areas extend across the primary crystallization fields of pyroxene and anorthite. There are obvious parallels between this variation and

the variation from ultrabasic to basic rocks.

The changing composition of olivine in the section illustrated in figure 14B would involve a variation in the lime content of the olivine. Comparison of the probable distribution of tie lines in figure 21 with the liquidus and solidus isotherms on the olivine join, figure 14A, shows that in fact very little lime would enter the olivine in natural rocks. A more detailed discussion of the effect of the plateau feature on the olivine join, if the tie lines were accurately known, would therefore lead to the same general conclusions, but the composition of the crystalline phase would be much closer to that of olivines actually present in picritic rocks.

If the plateau feature persists between ultrabasic and basic rocks in the complex multicomponent systems required to represent picrites and basalts completely, the three petrological processes which were referred to at the beginning of the section are:-

1. Crystallization of picritic liquids: cooling of a picritic liquid would result first in the rapid precipitation of many olivine crystals, rich in forsterite, whose composition would change relatively little.

2. Solution: basic liquids would be able to dissolve a considerable amount of forsteritic olivine crystals if the temperature of the liquid were raised slightly above a critical value.

3. Fusion: fusion of crystalline dunite or peridotite would produce first a basic liquid. As the temperature was raised, more olivine would pass into solution and a stage would be reached where there would be a rapid increase in the rate of solution of olivine.

The products of processes 2 and 3 would approximate picritic liquids

in composition. Much greater temperatures would be required to produce liquids approaching dunite in composition.

2. EVIDENCE RELATED TO THE MELTING TEMPERATURES OF THE SEDIMENT

2.1. Introduction

The first change noted with progressive metamorphism was the decomposition of sericite, which occurred about 40 cms. below the basal contact zone of Sill 1A. The breakdown of the muscovite structure in air has been described and interpreted by several mineralogists. Yoder and Eugster (1955) gave a brief account of earlier studies and concluded that the differing results reported suggest that the observed decomposition products were not equilibrium assemblages. They published detailed studies of the stability ranges of synthetic and natural muscovites in the presence of water vapour under pressure, taking care to ensure that equilibrium was attained, and their results permit an estimate of the temperature at which the muscovite in the sediment decomposed.

Reduction to magnetite of the hematite in the original sediment occurred at about the same level in the sediment as the decomposition of the muscovite. It is clear from the work of Muan (1955) on the system FeO-Fe_2O_3-SiO_2 that the reversible change hematite $\rightleftharpoons$ magnetite is dependent upon both temperature and the partial pressure of oxygen. A temperature estimate is available from the experimental studies on muscovite, and this provides some information about the nature of the fluxes present during the initial stages of fusion.

The former presence of tridymite in the fused sediments provides fairly well defined lower temperature and upper pressure limits for the metamorphism. Wager *et alia* (1951) doubt the usefulness of tridymite as a geological thermometer, because the inversion from quartz to tridymite is sluggish (Larsen 1929) and it is known from experimental

studies that tridymite may crystallize metastably outside its stability field (Fenner 1913). Other petrologists have not hesitated to use the presence or absence of tridymite in a rock to provide an indication of temperature (Thomas 1922, Davidson 1935, Black 1954b). It is now known that the inversion quartz $\rightleftharpoons$ tridymite proceeds quite readily in the presence of water vapour under pressure and tridymite crystallizes rapidly from melts only within its stability field (Tuttle and England 1955, Tuttle and Bowen 1958).

As stated earlier, the Torridonian sediment near Sills 1 and 1A is not true arkose, but is more correctly a feldspathic sandstone. Such sediments result from the weathering and transportation of granitic rocks and much of the original feldspar is decomposed during transportation (Williams et alia 1955). Selective fusion of a sediment produces first the lowest melting or "granitic" fraction and, with increasing temperature, the more refractory minerals are fused (Bowen 1928, pp. 175-223). Fused rocks behaving in this manner have been described by Allison (1936), Knopf (1938) and many others. The analysis of the fused sediment (specimen 129, tables 10 and 12) is too low in alumina and alkalis to correspond to a granitic rock (compare the average compositions of granitic rocks in Nockolds 1954), but the liquids produced by fusion would be granitic in composition until the excess quartz had also dissolved. The most useful diagram for the comparison of granitic rocks is that for Petrogeny's Residua System, nepheline-kaliophilite-silica (Bowen 1937) and the subsidiary system albite-orthoclase-silica. Liquidus temperatures have been determined for most parts of this system, and they provide an estimate of the temperature at which a given composition would be completely liquid. However, the sediments were fused in

the presence of volatiles, and temperatures estimated from the "dry" system would be too high. Tuttle and Bowen (1958) determined liquidus temperatures for the system albite-orthoclase-silica-water, and they compared the results obtained in this system with results obtained from experiments on natural granites in the presence of water vapour under pressure. The agreement between the synthetic system and the complex "magmatic" system is remarkably good. The effects of other volatile components in addition to water on the melting temperatures of natural granites have also been investigated (Wyllie and Tuttle 1957, Tuttle and Wyllie 1957). Some volatiles when added to water lower the temperature of beginning of melting of granite more than water alone, and the addition of others to water raises the temperature of beginning of melting. What the combined effect of several volatile components would be is not yet known. It is to be expected that volatiles from a hot magma would become concentrated in cooler areas, such as contact rocks and xenoliths, and Shepherd (1938) therefore considers that the volatile content of an altered rock will be a chance figure depending upon its past history. Later hydration of a glass may increase its volatile content (Ross and Smith 1955). Some equilibrium data are available on the solubility of water in silicate melts (Goranson 1931, 1938; Tuttle and Bowen 1958); the percentage of water vapour which dissolves in a melt depends upon the pressure, temperature and composition of the liquid. The solubility of P_2O_5 in silicate melts is not known. It is impossible, therefore, to make a reliable estimate of the temperature attained by the xenolith on the basis of its present volatile content, because there are too many variable factors.

2.2. The Early Stages of Fusion

The univariant equilibrium curve for the reaction: muscovite $\rightleftharpoons$ sanidine + corundum + vapour was determined by Yoder and Eugster (1955). At a pressure of 5,000 psi of water vapour, synthetic muscovite decomposes at 635°C and at a pressure of 30,000 psi the decomposition temperature is 715°C. On the basis of thermodynamic calculations they estimated that the decomposition temperature decreases to about 425°C for pressures lower than 5,000 psi.

Some water vapour would be present in the pores of the original sediment and the decomposition of the sericite in the sediment would therefore occur in the presence of water vapour under pressure. The maximum pressure on the rock during metamorphism (estimated below from phase equilibrium data) was 430 Kg/cm.^{2} (6,230 psi), and the decomposition of the sericite probably occurred below 635°C. None of the decomposition products was recognized in the matrix produced by the decomposition of the muscovite. Although the effect of the vapour released must have lowered the temperature of beginning of melting of the sediment, it would be unwise to place undue reliance on the estimated temperature, because the composition of the sericite is not known. Other micas, for instance phlogopite, remain stable to much higher temperatures (Yoder and Eugster 1954).

Osborn (1956) states that in air, hematite is stable between 500°C and 1390°C; at 1390°C, hematite is reduced to magnetite. This reaction occurs at lower temperatures with lower oxygen pressure and at higher temperatures with higher oxygen pressure. Since the muscovite decomposed at a temperature near 635°C, it must be concluded that the fluxes produced by the decomposition were strongly reducing in nature. The

preservation of hematite in feldspar crystals and composite quartz grains is undoubtedly due to their effective isolation from the interstitial flux.

2.3. The System Albite-orthoclase-silica-water

Figure 15 compares the compositions of fused rocks and the glasses contained within them in terms of normative albite, orthoclase, and quartz. The determined projections of isobaric cotectic boundaries in the system albite-orthoclase-silica-water (Bowen and Tuttle 1958) are also shown. The boundaries separate the primary crystallization fields of feldspar and a silica mineral (cristobalite, tridymite or quartz, depending upon the composition and the pressure), and the points M_1, M_2, and M_3 mark the positions of the temperature minima on the boundaries for water vapour pressures of 500, 1,000 and 2,000 Kg/cm.^{2}. The liquidus isotherms in the silica field are approximately parallel to the cotectic boundaries, and the temperature required to completely melt a given composition is lowered with increasing water vapour pressure. The temperature trough which exists near the minimum in the dry system (Schairer 1950) persists under pressure. Orthoclase melts incongruently to leucite, and the leucite field therefore extends into this system, but its presence does not affect the discussion.

The points 1 to 4 represent the composition of the analyzed fused xenolith from Sill 1 and the calculated compositions of liquids which existed within the xenolith at different stages of cooling (table 12). The specific gravities of the minerals involved in the calculations were obtained from Winchell and Winchell (1951) and the specific gravity of the glass was estimated (see Part II). For each analysis, normative

TABLE 12. CALCULATED COMPOSITIONS OF ORIGINAL LIQUIDS IN THE ANALYZED FUSED XENOLITH

	1	2	3	4	5
SiO_2	71.04	68.72	66.29	71.90	75.57
Al_2O_3	10.92	11.94	12.87	12.45	11.38
Fe_2O_3	2.14	2.34	2.52	-	0.82
FeO	1.48	1.62	1.74	-	1.63
MgO	2.22	2.43	2.62	-	0.72
CaO	1.34	1.47	1.58	1.89	1.69
Na_2O	2.96	3.24	3.49	4.18	2.45
K_2O	1.35	1.48	1.59	1.91	3.35
H_2O	4.48	4.90	5.28	6.32	1.06
H_2O -	0.52	-	-	-	0.05
TiO_2	0.68	0.74	0.80	-	0.42
MnO	0.07	0.08	0.08	-	0.05
P_2O_5	0.96	1.05	1.13	1.35	0.30
	100.16	100.01	99.99	100.00	99.49

1. Fused xenolith, specimen 129. See table 10.
2. Calculated composition of the liquid existing in the xenolith at the maximum stage of fusion. Analysis 1, less remnant quartz (see table 11).
3. Calculated composition of the liquid which would have existed in the xenolith if only tridymite had crystallized from the original liquid. Analysis 2, less inverted tridymite (see table 11).
4. Calculated composition of the liquid in the xenolith which was quenched to a glass, i.e. the composition of the glass. See table 10.
5. Average Torridonian arkose in south eastern Skye. (Average of three analyses by M. H. Kerr, in Kennedy 1951).

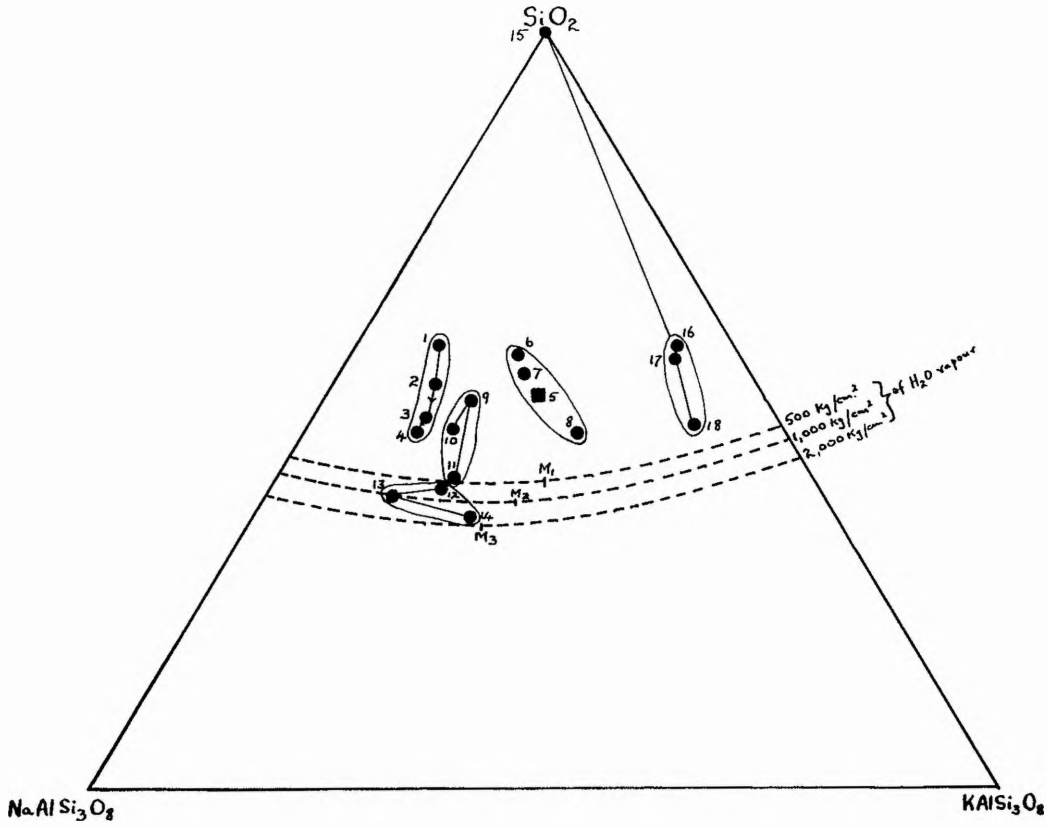


Figure 15. The compositions of fused rocks and their glasses plotted in terms of normative quartz, orthoclase and albite. Points 1 to 4, table 12. Points 6 to 8, analyses of Torridonian arkose; and point 5 the average of 6 to 8, Kennedy 1951. Points 9 to 11, Frankel 1950. Points 12 to 14, Larsen and Switzer, 1939. Points 15 to 18, Holmes 1936. The dotted lines are the projected isobaric cotectic boundaries for the pressures 500, 1,000 and 2,000 Kg/cm.^{2} in the system albite-orthoclase-silica-water (Tuttle and Bowen 1958). M_1, M_2 and M_3 are the minimum temperatures on these boundaries.

albite, orthoclase and quartz were recalculated to 100 per cent and plotted in figure 15. Point 1 represents the bulk composition of the fused xenolith and point 2 represents the calculated composition of the liquid in the xenolith at the stage of maximum fusion (the modal amount of quartz was subtracted from the bulk composition). This calculated analysis is believed to be accurate because the percentage of remnant quartz could be accurately estimated (table 11). The liquid 2 changed in composition as it cooled, precipitating crystals of tridymite, hypersthene, cordierite and magnetite. The point 3 represents the bulk composition of the xenolith less the remnant quartz and the inverted tridymite fringes, and the point 4 represents the approximate composition of the glass within the xenolith, i.e. the composition of the liquid when it was quenched (see Part II). The three points 6, 7 and 8 represent three analyzed Torridonian arkoses from south-eastern Skye (Kennedy 1951), and the point 5 represents the average of these three (table 12). According to Kennedy (1951) "the analyses are thoroughly representative of the formation", a fact apparent from the analyses and from a regional study of thin sections. The three analyses have distinctly higher potash/soda ratios than the fused xenolith (point 1) and, although the point 5 may be representative of the Torridonian sediments in Skye, the Soay rocks are known to show variation. The bulk composition of the fused xenolith is regarded as the best available estimate of the original composition of the sediment before metamorphism and fusion.

If a synthetic mixture of feldspar and quartz with bulk composition 1 (figure 15) were heated at a constant pressure of water vapour, the first liquid to develop would have the composition of the minimum on the

appropriate isobaric cotectic boundary. With increasing temperature, the liquid would increase in amount and change in composition, moving along the cotectic boundary, while quartz and feldspar dissolved. When all the feldspar had passed into the liquid phase, the tie line connecting the composition of the liquid to the solid phase, quartz, would pass through the bulk composition, 1. With further heating, more quartz would dissolve and the composition would change along the tie line, becoming progressively richer in silica until the charge consisted of liquid of composition 1. Petrographic study of the partially fused sediments confirms that this is the manner in which the sediment was selectively fused but, at the maximum stage of fusion, the sediment consisted of quartz and liquid of composition 2.

In the synthetic system, the liquid 2, on cooling, would change in composition along the tie line through SiO_2 and the point 2, with the precipitation of tridymite (or cristobalite or quartz, depending upon the composition of the remaining liquid and the pressure) until it reached the isobaric cotectic boundary. Tridymite would then be joined by feldspar, and feldspar and tridymite would crystallize together while the liquid composition changed along the cotectic boundary towards the minimum. The last trace of liquid would disappear when the tie line connecting the feldspar composition and SiO_2 passed through the point 2 (assuming equilibrium crystallization). In the fused xenolith, considering only the precipitation of tridymite, the liquid 2 would change in composition as far as the Point 3. In fact, the natural sample contained also minor amounts of magnesia, iron, and lime, and this resulted in the precipitation of cordierite, hypersthene and magnetite in addition to tridymite. The effect of these constituents caused the

liquid to change to the composition 4 (instead of 3) where it was quenched to a glass. The points 3 and 4 are not far apart, confirming that the influence of small amounts of cafemic oxides is very slight. The lines connecting the compositions 1, 2, 3 and 4 are very close to the tie line connecting SiO_2 and the composition 1.

The behaviour of the sediments with progressive metamorphism and fusion, and the change in composition of the liquid with cooling is very similar to that expected from consideration of the synthetic system, and this justifies the use of the system for the comparison of the metamorphosed products with similar rocks. Analyses of glass in xenoliths of quartzose rocks enclosed in basic or ultrabasic igneous rocks from three other localities are plotted for comparison.

Frankel (1950) described the fusion of feldspathic sandstones by dolerite intrusions. Point 9 represents the composition of a glassy xenolith and point 10 represents a calculated analysis of the glass within the xenolith. The composition of the glass separated from a fused inclusion in a different intrusion is represented by the point 11. No analysis of the original sediment is available, and the composition of the fused xenolith (9) must be considered the best estimate of the original composition. The relative positions of the fused xenolith (9) and the quenched liquids (10 and 11) are similar to those determined for the xenolith in Sill 1. The tie line through SiO_2 and the point 9 is almost parallel to the lines connecting the bulk composition of the fused xenolith (9) to the glasses produced by fusion (10 and 11), and the presence of inverted tridymite fringes confirms that the liquid present in the xenolith at the stage of maximum fusion changed in composition down the liquidus surface of the silica field.

Larsen and Switzer (1939) analyzed the glass (point 14) formed by fusion of a tonalite inclusion enclosed by olivine basalt. The ratio of potash to soda is lower in the fused xenolith (point 13) than in the parent tonalite (point 12) but the difference is so slight that the authors ascribe it to differences in the original tonalite. The selective fusion of a synthetic mixture of composition 13 would produce first a liquid at the minimum on the appropriate isobaric cotectic boundary, and this would change in composition along the cotectic boundary approaching the bulk composition as feldspar and silica pass into the liquid phase. The line joining the glass (point 14) to the fused xenolith (point 13) is directed approximately along the cotectic boundaries, as expected from consideration of the synthetic system. Cooling and crystallization of the liquid produced at the stage of maximum fusion would cause the liquid to change in composition down the cotectic boundary towards the minimum, with the crystallization of feldspar and a silica phase, until it was quenched to a glass. Tridymite was not recognised (temperature below 870^{o}C, Larsen and Switzer 1939) but microlites of plagioclase feldspar are present in the glass.

Holmes (1936) described the development of glass around and within pure quartzite xenoliths immersed in ultrabasic potassic lavas. Point 15 represents the quartzite xenoliths, and points 16, 17 and 18 represent the compositions of analyzed glasses. It is clear from the compositions of the xenoliths and the glasses that the process was not direct melting, but involved also the migration of material from the lava to the xenoliths. The differential migration of material was described in detail by Holmes (1936). These glasses will be discussed later in connection with other metasomatic rocks.

The calculated compositions of the original liquid and the quenched liquid in the fused xenolith of Sill 1 (analyses 2, 4 and 1, respectively, table 12 and figure 15) permit an estimate of the temperature of the xenolith between the stages of maximum fusion and quenching of the liquid (the interval AB-CD in figure 12). The temperature at which any mixture in the system albite-orthoclase-silica-water would be completely liquid will depend upon the composition of the mixture and the pressure of water vapour. Normative albite, orthoclase and silica for the fused xenolith and calculated glasses of Sill 1 amount to more than 80 per cent of the rocks (omitting water). The combined effect of the remaining oxides on the liquidus temperature of the original sediment cannot be estimated from available experimental evidence, but there is evidence that their effect would be small.

Schairer (1957) recently published a useful summary of the phase relations in Petrogeny's Residua System and in ternary systems combining one of the early crystallizing minerals in rocks with the late crystallizing alkali aluminosilicates of the Residua System. The addition of, for example, diopside to the Residua System would produce the quaternary system nepheline-kaliophilite-diopside-silica which can be represented as a tetrahedron. The silica field in the ternary Residua System would extend upwards into the quaternary tetrahedron as a silica space, which would be partially bounded by the silica fields of the Residua System and of the studied systems leucite-diopside-silica (Schairer and Bowen 1938) and nepheline-diopside-silica (Schairer 1957). Liquidus isotherms in the silica fields of the latter two systems, if extended from the joins leucite-silica and nepheline-silica respectively would pass very close to the composition diopside. This means that the addition

of diopside to the binary systems leucite-silica or nepheline-silica would cause very little change in the liquidus temperatures of mixtures for which a silica mineral was the primary phase. The other diagrams reproduced by Schairer (1957) show that the effect of anorthite and forsterite are similar to that of diopside, and it seems reasonable to assume that similar relations pertain within the quaternary silica spaces bounded by the silica fields of the several ternary systems. It may be concluded from the phase equilibrium data that the addition of minor amounts of diopside, anorthite and forsterite to synthetic mixtures represented by the points 1 to 4 in figure 15 would change the liquidus temperatures only slightly. Confirmation is available from the study of more complex "magmatic" systems: (1) Tuttle and Bowen (1958) showed that in the presence of water vapour under pressure, the temperatures of beginning of melting of natural granites, containing an excess of cafemic oxides compared to the synthetic system albite-orthoclase-silica-water, are almost identical with the minimum melting temperature of mixtures in the synthetic system. It is unlikely that the effect of the excess oxides on liquidus temperatures would be any greater. (2) It was shown above that the fusion and subsequent crystallization of the sediments was changed only slightly by the presence of cafemic oxides in addition to the components of the synthetic system. It is therefore considered justifiable to consider the analyses only in terms of normative albite, orthoclase and silica.

The analysis of the fused xenolith confirms that the fusion occurred in the presence of abundant water vapour but other volatile components may have been present as well. Some P_2O_5 was certainly present (table 12) but its effect on liquidus temperatures is not known. Since no

independent estimate of pressure is available, no definite estimate of liquidus temperatures for the calculated liquid compositions can be made because the liquidus temperature for a given composition varies with the pressure of water vapour. The "equilibrium" temperatures at which the calculated compositions 2 and 4 would be completely liquid at different pressures of water vapour can be estimated from the determined isotherms in the isobaric projections of the system albite-orthoclase-silica-water (Tuttle and Bowen 1958).

The liquidus temperature of the quenched glass, composition 4, figure 15, was estimated in this way for the pressures 500, 1,000 and 2,000 $Kg/cm.^2$, and the dry liquidus temperature was estimated from isotherms in the system albite-orthoclase-silica (Schairer 1950). A PT curve drawn through the four determined points gives a projection of the liquidus for this composition. Part of the PT projection, DC, is shown in figure 16, and this represents the possible range of conditions at which the liquid in the xenolith would have been quenched to a glass (compare the point CD in figure 12). If the pressure were known, the temperature could be determined from the curve. The calculated composition of the original liquid in the fused xenolith (composition 2, figure 15) is beyond the range of determined liquidus isotherms in the hydrothermal system, but the liquidus temperature may be determined in the dry system. The temperature interval on the liquidus of the dry system between the compositions 2 and 4 is $90^{o}C$. Assuming that the shape of the liquidus surface in the dry system for this compositional range does not change significantly with increasing water vapour pressure, the curve BA extended in figure 16, $90^{o}C$ higher than the curve CD at each pressure, is the PT projection for the liquidus of composition 2. This

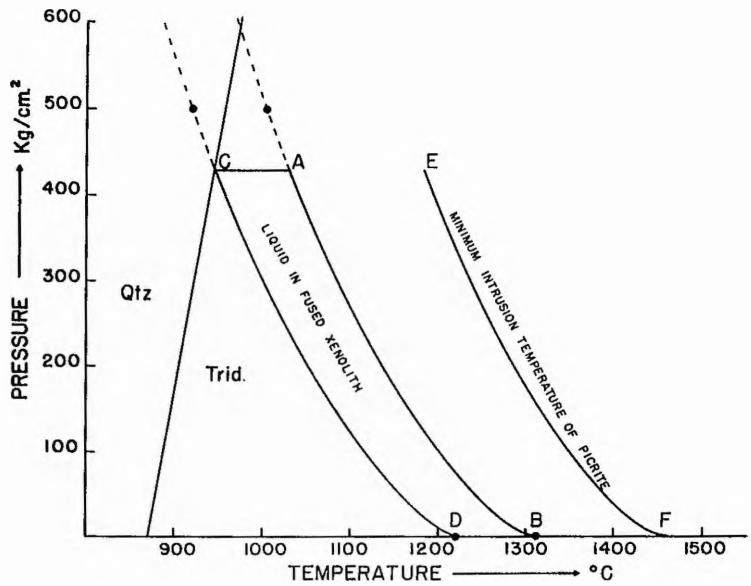


Figure 16. Estimated PT curves: CD, for the liquid present in the fused xenolith of Sill 1 when it was quenched to a glass; AB, for the liquid present in the xenolith at the stage of maximum fusion; EF, for the picrite magma when it was intruded. The experimentally determined PT curve for the inversion quartz ⇌ tridymite, in the presence of water vapour, is also shown. The PT curves AB and CD correspond to the points AB and CD in figure 12.

corresponds to the stage of maximum development of liquid within the xenolith, as represented by the point AB in figure 12. At a fixed pressure the temperature interval between the curves AB and CD in figure 16 corresponds to the temperature interval AB-CD in figure 12.

Tridymite, cordierite, hypersthene and magnetite crystallized from the liquid as it cooled from the PT conditions represented by the curve AB to those represented by the curve CD. Crystallization of tridymite proves that the liquid was within the stability field of tridymite when it started to cool, and the relatively high proportion of inverted tridymite present in the fused xenolith suggests that it remained there

until it was quenched. The experimentally determined PT projection of the quartz-tridymite inversion is plotted in figure 16 (Tuttle and England 1955, Tuttle and Bowen 1958), and its intersection with the curve CD gives the maximum pressure on the xenolith during fusion, 430 Kg/cm.^{2}. If the pressure were greater than this, tridymite would not have crystallized from the liquid throughout its cooling interval and, if the pressure had been greater than 600 Kg/cm.^{2} (the intersection of the curve AB extended with the quartz-tridymite inversion curve), tridymite would not have crystallized from the liquid at all. The area ABCD in figure 16 thus represents the probable range of pressures and temperatures from the stage of maximum development of liquid in the xenolith to the stage when the remaining liquid was quenched to a glass. The maximum pressure, 430 Kg/cm.^{2}, corresponds to a depth of intrusion of about 1.7 kms., assuming a superincumbent load of sediments with average density 2.5. If the sill was emplaced at this depth, the maximum temperature reached by the liquid in the xenolith would be about 1025^{o}C, represented by the point A, figure 16. (Before the stage of maximum fusion, the liquid could have reached a slightly higher temperature, but the liquid present would not have been in equilibrium and therefore cannot be considered in relation to the synthetic system. See figure 12 and the discussion in Part II). If the sill was emplaced nearer to the surface, the maximum temperature would be higher, the temperature corresponding to any pressure being given by the curve CD.

It should be emphasised that this estimate of the PT conditions accompanying the fusion of the xenolith is based only upon the available phase equilibrium evidence for the dominant constituents of the natural system, namely orthoclase, albite, silica and water. It has been shown

that the effect of other silicate components is unlikely to change the conditions greatly but the effect of P_2O_5 and other volatile components which may have been present cannot be assessed. Use of the quartz-tridymite PT projection is believed justifiable, but it is possible that the tridymite crystallized metastably.

In Part II, it was concluded that the maximum activity of the fused sediments, i.e. the stage of maximum development of liquid, probably occurred at least 150°C below the intrusion temperature of the picrite. The PT curve EF in figure 16 is 150°C higher in temperature, at a given pressure, than the curve AB which represents the conditions of maximum fusion in the xenolith. The curve EF therefore represents the estimated range of minimum intrusion temperatures of the picrite, the actual temperature depending upon the depth of intrusion. If the picrite was emplaced at a depth of 1.7 kms., its estimated intrusion temperature was at least 1175°C (E), and if it was emplaced at shallower levels in the crust, the minimum intrusion temperatures would range from 1175°C to 1460°C (F), depending upon the depth of emplacement. These estimated temperatures are considerably higher than the temperatures of intrusion of normal basaltic rocks. For instance, Walker and Poldervaart (1949) estimated that the Karroo dolerites were intruded at temperatures between 1100°C and 1150°C.

2.4. The Fusion and Metasomatism of Siliceous Xenoliths

It is the purpose of this section to compare the products of fusion of xenoliths with the products of metasomatism. Quartzite xenoliths in basic magmas are often partially feldspathised and well-documented evidence proves that in some cases there was differential movement of

oxides or elements from the magma into the xenoliths (e.g. Holmes 1936, Reynolds 1936, 1938). The feldspathic products are therefore metasomatic in origin, although Holgate (1954) considered that the differential migration of oxides resulted from a process involving liquid immiscibility. The fused xenoliths previously described, together with analyses of metasomatic rocks from the literature, are plotted in figure 17. All points represent normative quartz, orthoclase and albite, recalculated to 100 per cent. The total of these normative constituents exceeds 70 per cent of the rocks, except for an appinite (point 30) and a syenite intrusion (point 31). The points 1 to 18 were discussed in section 2.3.

Wager et alia (1953) described a granophyre from Skye which contained quartz paramorphs after tridymite. Whereas the analyses of other Skye granites are clustered around the ternary minima (M_1 to M_3), analyses of the granophyre and its chilled margin (20 and 19) are nearer to the silica pole. The analyses are close to the average composition of the Torridonian arkose in south-eastern Skye (point 5), and the former presence of tridymite in the granophyre is distinctive. In this respect, it resembles the fused sediment within and near to Sill 1A. Wager et alia (1953) concluded that the granophyre may have originated by fusion of Torridonian arkose or Lewisian gneiss, and fusion of the arkose (5) could certainly produce a liquid near the points 19 and 20 in composition. A metasomatised quartzite xenolith (21) in gabbro at Ardnamurchan (Wells 1951) is very similar in composition to the Skye granophyre (19 and 20), but this is probably a coincidence. A single analysis is of little use in discussing petrogenetic processes, but examples of metasomatism, in which trends can be distinguished, are available.

The glasses 16, 17 and 18 were produced by the metasomatism of

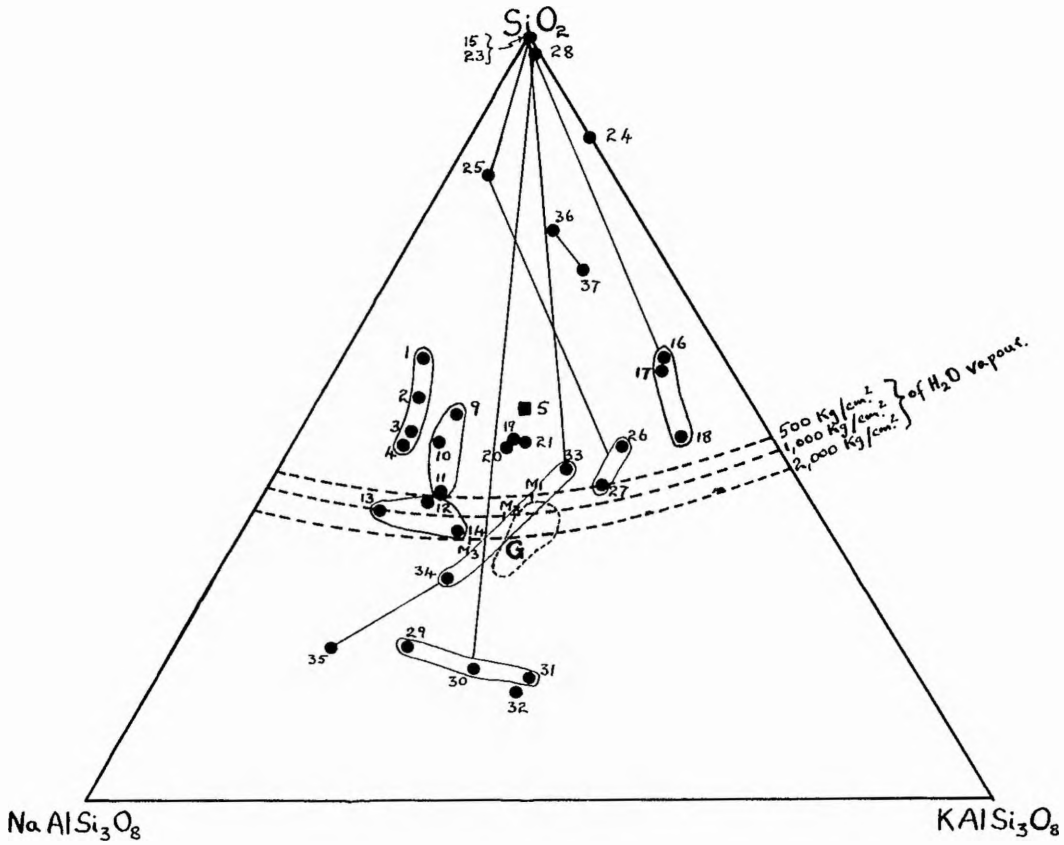


Figure 17. The compositions of fused xenoliths, glasses contained within fused xenoliths, and feldspathic rocks produced by metasomatism compared in terms of normative quartz, orthoclase and albite. The points 1 to 18 are reproduced from figure 15; 19 and 20 from Wager et alia, 1953; 21 from Wells 1951; 23 to 27 from Daly 1928; 28 to 32 from Reynolds 1936; 33 to 35 from Reynolds 1938; 36 to 37 from Reynolds 1940. The area G contains about 30 per cent of the granitic rocks listed by Washington which contain more than 80 per cent of normative quartz, orthoclase and albite (Bowen and Tuttle 1958). The dotted lines are the projected isobaric cotectic boundaries in the system albite-orthoclase-silica-water, see figure 15.

quartz xenoliths (15) immersed in ultrabasic, potassic lavas (Holmes 1936). The analyses lie in the silica field of the synthetic system, and their compositional trend is approximately perpendicular to the isotherms on the liquidus surface. Daly (1928) gives several analyses of quartzite xenoliths from the Bushveld complex which have been progressively metasomatised into feldspathic rocks. Three analysed xenoliths consist of almost pure quartz (23), and a fourth contains 4 per cent of K_2O, as well as some Fe_2O_3 and MgO (24). Analysis 25 is described as a slightly feldspathised xenolith, and 26 and 27 are strongly feldspathised. The point 37 is the metamorphosed and metasomatised equivalent of the sandstone 36, which is in contact with a dolerite dyke (Reynolds 1940). The trend from 36 to 37 is almost parallel to that from the pure quartz xenoliths (15) to the glasses 16 - 18, and to that from the slightly feldspathised xenolith 25 to the strongly feldspathised xenoliths 26 and 27. The products remain in the silica field of the system. Other examples of metasomatism demonstrate different trends.

Reynolds (1936) described the formation of syenite and appinite rims by the metasomatism of quartzite xenoliths enclosed by hornblendite intrusions. The point 28 represents the residual core of a quartzite xenolith, and points 30 and 31 respectively represent syenite and appinite rims. Analysis 29 is a syntectic syenite pegmatite (of metasomatic origin), and Reynolds suggested that a nearby syenite intrusion (32) was produced by metasomatism on a larger scale. These rocks lie in the feldspar field of the synthetic system, and have therefore crossed the cotectic boundary with progressive metasomatism. The variation in composition from 29 to 31 is approximately parallel to the liquidus isotherms of the synthetic system.

The points 33 and 34, which are feldspathic rims developed around quartzite xenoliths in lamprophyre dykes (Reynolds 1938), straddle the cotectic curves. The point 35, an alkali feldspar porphyry dyke, associated with the lamprophyres, is also considered to be a metasomatic product, and this is further within the feldspar field in the direction indicated by points 33 and 34.

The relationships between the metasomatised xenoliths and the enclosing magmas have been discussed by the various authors and need not be reconsidered. The important fact which emerges is that, after their initial change in composition away from pure silica, the metasomatised products bear no simple relationship to the cotectic boundary, or to the liquidus surfaces of the synthetic system. On the other hand, the fusion of the xenoliths 1, 9 and 13 proceeded in a manner which could be predicted by consideration of the synthetic system. The presence of cafemic oxides in addition to the three components considered has modified their behaviour only slightly. It is now well established that the compositions of granitic rocks expressed in terms of modal or normative quartz, orthoclase and albite are highly concentrated near the ternary minimum of the system albite-orthoclase-silica (Chayes 1952, Tuttle and Bowen 1958). The area G includes about 30 per cent of all granitic rocks (with normative q + or + ab $>$ 80 per cent) listed by Washington (Tuttle and Bowen 1958). Moreover, granitic rocks which are genetically related always lie on the same side of the low temperature trough, and this is strong evidence that their evolution was dominated by crystal $\rightleftharpoons$ liquid equilibrium (Chayes 1952).

Advocates of a metasomatic origin for granite must assume that the products of metasomatism coincide with the remarkable concentration G.

Evidence from the metasomatised xenoliths suggests that the process of metasomatism does not lead to a concentration of products in the area G. The products are widely spaced in composition, and bear no special relationship to the low temperature trough or the field boundaries of the synthetic system, in which the granites are concentrated. The starting material in each case was almost pure quartz and, with variation in composition of the original material, the range of compositions produced by metasomatism would certainly increase. It would be interesting to compare the compositions of other granitic rocks, whose metasomatic origin is reasonably established, with the compositional trends of the metasomatised xenoliths. If these trends are confirmed, it seems improbable that the bulk of granitic rocks could be metasomatic in origin.

PART IV

PETROGENESIS

1. THE SIGNIFICANCE OF THE VARIATIONS IN SHAPE AND SIZE OF OLIVINE CRYSTALS

1.1. The Shapes of Olivine Crystals

The diversity of shapes exhibited by the olivine crystals in Sills 1 and 1A was briefly described and illustrated in Part I and it was concluded, in agreement with Drever and Johnston (1957), that all of the observed shapes could have developed by preferred growth along the two crystallographic directions 'a' and 'c', combined with incomplete inward growth. There are gradations between crystals with undoubted skeletal form and crystals showing normal crystal outlines. Drever and Johnston (1957) published a detailed review of the crystal growth of forsteritic olivine in magmas and melts, and many of the forms they described can be matched by examples in Sill 1 and 1A. They discussed the significance of these shapes and further discussion would be merely repetitive. The writer endorses their conclusion that: "What is now beyond reasonable doubt is that large phenocrysts of olivine can crystallize in situ." No criteria were found from their wide survey by which skeletal forms of possible derivative origin could be distinguished with certainty from those which may have crystallized in situ, and the allocation of manifestly skeletal crystals to a "first" or "second" generation they regarded as quite arbitrary. Therefore, no attempt will be made to account for the diversity of shapes recorded until other evidence is discussed.

1.2. The Size Variation of Olivine Crystals

Sills 1 and 1A contain large phenocrysts of olivine contrasting sharply in size with the feldspar, pyroxene and olivine of the groundmass. The texture is porphyritic but statistical analysis of the size

distributions of olivines in Sill 1 demonstrates a gradation in size from the large phenocrysts to the small olivine crystals related in size to the groundmass (Part I).

One of the major arguments advanced by Bowen (1928) in support of his theory of crystal accumulation for the origin of olivine-rich rocks is that picrites and olivine basalts are characterized by large phenocrysts of olivine. He concluded (page 164) that:

> "....if one finds the condition shown by these basalts to be invariably true of all rocks which have sufferred quenching, one must conclude that large amounts of olivine never occur in solution in magmatic liquids. A survey of igneous provinces leaves no question that such rocks do have this character, that is, they always contain all of their olivine or all in excess of a quite small amount (apparently some 12 or 15 per cent) as relatively large phenocrysts."

This conclusion is based on the recognition of two "generations" of olivine distinguished by a size difference and the discussion concerns, in particular, the ultrabasic minor intrusions of Soay and Skye. Critical re-examination of Bowen's conclusions is required in the light of the review of existing evidence and the presentation of new evidence by Drever and Johnston (1957).

The term "porphyritic texture", as used by petrologists, includes several textural relationships which, although similar, may have different genetic implications. The Glossary of Geology and Related Sciences (Trowbridge 1957) defines "porphyritic" as:

> "a textural term for those igneous rocks in which larger crystals (phenocrysts or insets) are set in a finer grained groundmass which may be crystalline, or glassy, or both."

By this definition the term has no genetic meaning. Harker (1909, p. 262) defined the texture as the occurrence of the same constituent of a rock in two distinct generations, with phenocrysts of notably larger dimensions, referable to distinct stages in the consolidation of a magma. He

therefore gives the term a definite genetic connotation. In his opinion, a rock containing phenocrysts without a second generation of the same mineral should not be described as porphyritic (p. 218). He cites the conspicuous size of olivine crystals in many basalts as an example and attributes their presence to specific growth properties of the mineral. To Tyrrell (1926, p. 88) the recurrence of the porphyritic element in a second generation is not necessary for a definition of porphyritic texture and he points out that the texture may arise in several different ways. Other petrologists (Hawkes 1930, Grout 1932, Shand 1947, Turner and Verhoogen 1951) stress the fact that although a sharp break in grain size may arise from interruption of crystallization at depth by eruption, it could also result from an even rate of magmatic cooling. Phenocrysts could represent initial slow crystallization from a slightly undercooled magma immediately after intrusion, while the finer groundmass could correspond to more rapid spontaneous crystallization as the magma became undercooled sufficiently to pass from a metastable to a most unstable condition (Turner and Verhoogen 1951). According to Hawkes (1930), the viscosity of a liquid magma increases with increasing undercooling and in a narrow temperature interval it increases very rapidly. Passage through this temperature interval could produce a sharp break in grain size. Bowen (1914, p. 257) demonstrated experimentally that certain synthetic mixtures give rise to the crystallization of olivine in two generations during regular cooling of a melt and he warned petrologists that a mineral may give the appearance of crystallization in two generations although crystallization was perfectly continuous. A porphyritic texture may therefore develop by different processes, and it must be considered as a descriptive term. Before it is

given a genetic sense there must be established first criteria for interpretation.

The tendency of geologists to neglect processes in the interpretation of textures is admirably expressed by Walton (1957). "Geology" may be stated operationally as $S = f(C,P)$. S is the possible sequential array of past configurations, C represents information on content, state and configuration, and P represents information on processes. The interpretation of porphyritic texture in olivine rich rocks is a good example of the misuse of this equation. If a rock contains phenocrysts of olivine as well as small crystals, petrologists almost invariably conclude that the olivine crystallized in two generations and to the phenocrysts is assigned an origin by accumulation, either in situ or in a deep seated magma chamber. Rarely is an attempt made to establish the fact that the phenocrysts belong to a generation distinct from the groundmass olivine, and rarely is any other origin considered as a possibility. The configuration C is equated to the process P, but without establishing that there is a distinct grouping into two size ranges knowledge of the configuration C is itself incomplete. The geologic equation is thus solved knowing less than one half of the parameters P and C. Of the published examples in which phenocrysts of olivine have been equated with a "first generation" there are many in which there is reasonable doubt concerning the accuracy of this solution of the geologic equation.

Harker (1904, p. 378) described the porphyritic development of olivine in a later peridotite of Skye in which the separation into two distinct generations was somewhat obscured by the occurrence, in addition, of crystals of intermediate grain size. Elsewhere (p. 384), he described

two generations of olivine which were not clear because the first generation became smaller towards the margin of the sill. In a variolitic picrite illustrated by Walker and Poldervaart (1949, figure 11), olivine phenocrysts are believed to result from early crystallization and accumulation within the intrusion. In the figure, however, there are many olivines intermediate in size between the phenocrysts and groundmass crystals and the distinction between them does not appear to be sharply defined. Olivine crystals in lavas of the Pacific are generally grouped into two generations (Macdonald 1949) and the phenocrysts are believed to have originated by intratelluric crystallization, but the distinction between the two "generations" is not always clear. For instance, Macdonald (1944) reported that the olivine of a basaltic andesite occurred as phenocrysts, microphenocrysts and groundmass crystals. This suggests either that there are not two, but three generations, or that there is a gradation in size between the large and small crystals. He confirmed the latter alternative for some rocks by the statement that a few olivine phenocrysts, 7 mm. long, grade in size into the groundmass. Drever (1956) described picritic sheets in which the olivine "tends to occur in two generations", but he referred to phenocrysts, microphenocrysts and groundmass crystals. This implies the presence of three rather than two generations but in figure 6, a thin section of the rock, there appear to be olivine crystals of all sizes. Drever and Johnston (1957) later suggested that such an appearance might be produced by the rapid crystallization of olivine crystals of varying sizes before final intrusion. Frankel (1942) measured the lengths of olivine crystals in an olivine dolerite of the Karroo region and his results suggest a gradation in size of the olivine crystals from large to small. Wilson (1948)

described an olivine dolerite containing olivine phenocrysts up to 1.6 x 1.6 mm. in size. He concluded that the olivine continued to crystallize to the end where it occurred with later minerals as small sphenoid particles only 0.1 x 0.1 mm. This implies that the size of the olivine crystals decreased regularly with progressive crystallization. Johnston (1953) reported a complete gradation in size from large to small crystals of olivine in the picrite of the Garbh Eilean sill in which olivine forms 61 to 66 per cent of the rock.

These examples indicate that the separation of olivine crystals into two distinct size groups, with the inevitable assumption that they represent two generations of olivine, is not always well founded. In view of the petrogenetic importance of olivine an impression of a break in grain size between phenocrysts and groundmass crystals should not be accepted as evidence of discontinuous crystallization without supporting evidence. If there is complete gradation in size from the olivine phenocrysts to groundmass crystals, a reason should be sought to explain why some olivine crystals were able to attain such large sizes. This is readily found in the low viscosity of magnesia rich melts and the rapid rate of crystallization of olivine (Drever and Johnston 1957).

It may also be established that the amount of olivine related to the groundmass (the "second generation") is not always less than the 12 to 15 per cent admitted by Bowen (1928). In the variolitic picrite of the Elephant's Head Dyke, phenocrysts of olivine constitute 30 per cent of the rock and groundmass olivine constitutes 23 per cent of the rock (Poldervaart 1944). In an olivine dolerite sill containing 18 to 20 per cent of olivine crystals, Wilson (1948) considered that all the olivine crystallized in situ. The normative olivine of an analyzed non-

porphyritic zone in a picrite intrusion amounts to 21.37 per cent (Drever and Johnston 1958). This zone is uniformly aphanatic and according to Bowen's (1928) criteria it represents an original liquid. In specimen 49 from Sill 1 on Soay, about 40 per cent of the rock is composed of olivine crystals definitely related in size to the groundmass (Part I). Drever (1956), on the basis of a study of picritic sheets in West Greenland, concluded that the possibility should be considered of an extension of true magmatic liquids beyond Bowen's (1928) limits. He believed that magma from which at least 25 per cent of olivine can crystallize is a widespread and important type. The present review confirms that an extension of Bowen's limits is required.

Before any attempt is made to interpret a porphyritic texture, the presence or absence of two generations of olivine must first be established. Two generations can be recognized only if there is some distinct difference between them, corresponding to a break in crystallization or to an abrupt change in physical or chemical conditions during crystallization. Crystal habit, chemical composition or crystal size are the properties most likely to change. Olivine crystals may show a wide variation of habit in the same rock (Kuno 1950, Drever 1956), but it is rare that a particular habit is confined either to phenocrysts or to groundmass crystals. A compositional difference between phenocrysts and groundmass crystals is often recorded but the difference is not always large compared to the accuracy of optical determinations. For instance, Poldervaart (1944) gave the composition of phenocrysts in a variolitic picrite as Fa_{15}, and the composition of groundmass crystals as Fa_{17}. Johnston (1953) described a picrodolerite with two generations of olivine (distinguished by a size difference) with an average compositional

difference of 1 per cent fayalite. Larger compositional differences are, however, not uncommon. In the Palisade sill olivine-ledge the composition of olivine phenocrysts is Fa_{20} and that of the groundmass olivine Fa_{30} (Walker 1940). Macdonald (1949) recorded a large compositional difference between the phenocrysts (Fa_{18}) and the groundmass crystals (Fa_{36}) of picrite basalts in the Pacific. The recognition of two generations of olivine crystals is sometimes made possible by a change in chemical conditions resulting from a discontinuity in the cooling history of a magma. Ross and Shannon (1925) described the occurrence in lavas of large phenocrysts of olivine which were completely altered to iddingsite, while small groundmass crystals of olivine showed little alteration. Cores of iddingsite were often surrounded by fresh olivine. Edwards (1938) concluded that the formation of iddingsite results from an oxidation process caused by the liberation of volatile materials during the uprise of a magma towards extrusion. The fresh olivine rims and unaltered groundmass crystals represent a second generation of olivine crystallized after extrusion and escape of the volatiles. Many similar examples occur among Pacific lavas (Macdonald 1949).

It was stressed by Bowen (1928) that olivine rich rocks generally contain large crystals which must be described as phenocrysts or insets, and the texture is therefore porphyritic. But only if the crystallization of the phenocrysts and groundmass olivines can be referred to distinct physical environments does it seem justifiable to relate them to different "generations". This could occur as a result of (1) early crystallization of a first generation of olivine at depth, followed by the crystallization of a second generation after eruption, or (2) settling of early precipitates of olivine under the action of gravity, followed

by the crystallization of a second generation of olivine crystals from the interprecipitate liquid (Walker 1940, Brown 1956), or (3) crystallization *in situ*, if the cooling magma passed through a stage of rapid increase in viscosity (Hawkes 1930). A second generation of small olivine crystals could then crystallize in a different physical environment. Only if there is an abrupt change in physical or chemical properties between phenocrysts and groundmass crystals can it be concluded that the olivine crystallized in two generations, and there remains the possibility that the two generations could be related to distinct physical environments resulting from continuous cooling and progressive crystallization of a liquid magma.

Returning now to the olivine crystals of Sill 1, there is little evidence that they crystallized in two generations (see Part I), and the presence of olivine phenocrysts in the sill cannot therefore be used as an argument to support Bowen's (1928) contention that the picrite was intruded in a largely crystalline condition. It is possible that the six largest phenocrysts of specimen 49, amounting to 14.5 volume per cent of the rock, represent a first generation of olivine crystals, but the remaining 39.5 volume per cent of olivine appears definitely to be related in size to the groundmass. The decrease in size and number of the largest phenocrysts from specimen 49 towards the margin of the sill suggests, however, that even the largest olivine phenocrysts are related to a single size distribution of olivine crystals. This suggestion is supported by the fact that similar parallel growths and skeletal crystals occur in both large and small crystals.

Drever and Johnston (1957) concluded that large olivine phenocrysts can crystallize *in situ* and the simplest interpretation of the size distributions of olivine in Sill 1 is that all of the olivine crystals

were precipitated essentially *in situ*, during a single cycle of cooling and crystallization. There are obvious difficulties facing this hypothesis and they will be discussed in section 4. Although Drever and Johnston (1957) believed that interpretation of the growth characteristics of olivine crystals in picrite intrusions was unprofitable because of the many unknown factors, the additional statistical evidence for the olivine crystals of Sill 1 justifies a tentative interpretation. In the present discussion it is assumed that the picrite was emplaced as a liquid magma (see section 2), and the probable size distribution of the olivine crystals precipitated from such a liquid with regular cooling can be estimated.

Turner and Verhoogen (1951, p. 42 - 44) give a succint account of modern ideas on nucleation and rates of crystallization of new phases. A certain amount of undercooling is required to initiate crystallization in a liquid magma and the amount of undercooling required depends upon a number of factors. These vary in relative importance from one liquid to another and none of them is adequately known for magmas. If a magma is cooled, only a few nuclei are formed at first and, for slight undercooling, only large crystals are stable. With increasing undercooling the number of nuclei increases, the viscosity of the liquid increases and the rate of diffusion decreases. Therefore, with falling temperature, the number of crystals initiated would probably increase rapidly but the crystals would not grow as large as those already present in the liquid. The increase in the number of centres of crystallization with undercooling was investigated experimentally by Doelter (1905). The number of augite crystals growing in a slightly undercooled liquid (the metastable region) was very small. With further cooling the liquid passed into the

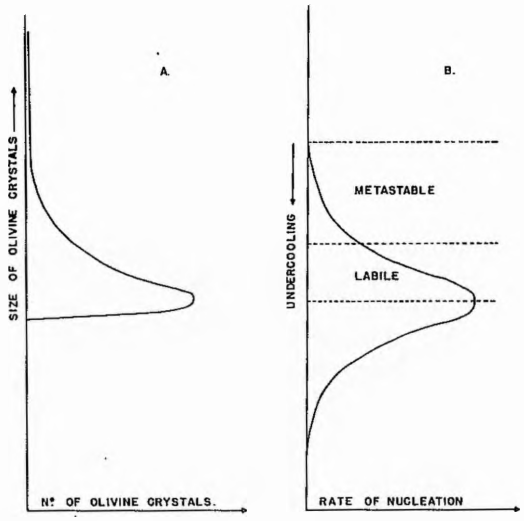


Figure 18. A. A frequency distribution curve for the observed size variation in the olivine crystals of Sill 1 (see figure 5). B. Experimentally determined curve showing the rate of nucleation of augite crystals in a supercooled liquid (after Doelter 1905).

labile region and the rate of formation of nuclei increased rapidly, passed through a maximum and then decreased. Tamman (1925) showed that the number of centres of crystallization reached a maximum in a region of abnormal viscosity increase which was later discussed by Hawkes (1930).

From the preceding remarks it seems a valid assumption that the size of an olivine crystal precipitated from a hypothetical picritic liquid would give an indication of the stage of cooling at which it crystallized. In figure 18, Doelter's (1905) diagram is compared with the size frequency distribution diagram for the olivines of Sill 1. The size of an olivine crystal represents the temperature (or degree of undercooling) at which it started to grow, and the frequency axis represents the number of centres of crystallization initiated at any degree of undercooling. The two diagrams are very similar in general form with decreasing

temperature and size of olivine crystals until the maximum on each curve is passed. The part of the size distribution curve which is asymptotic to the size axis corresponds to the metastable region, and the rapid increase in the number of smaller crystals corresponds to the increase in the number of nuclei developed in the labile region. It appears that the metastable region of the olivine is greater than that determined by Doelter for augite, but this may be accounted for by the specific properties of olivine. The size of olivine crystals would not bear a simple ratio to the degree of undercooling and it is probable that the growth rate of olivine in a liquid of low viscosity would permit the early formed crystals to attain very large sizes. In Doelter's experiments the liquid was quenched to a glass containing small crystals of augite, but the hypothetical picritic liquid crystallized completely. The crystallizing olivine was eventually joined by feldspar and pyroxene. The textural relationships of the feldspar and pyroxene suggests that they grew rapidly from a number of nuclei at a stage when the olivine had reached the labile region. Because the final liquid crystallized to feldspar and pyroxene as well as olivine, the number of new centres of crystallization of olivine inevitably decreased. This fact may account for the difference between the two diagrams in figure 18.

Little size variation appears to have developed in the feldspar and pyroxene and this may be due to their rapid crystallization from a limited quantity of liquid. At the chilled margins of the sill the cooling was even more rapid, and only olivine had an opportunity to grow. More rapid passage through the metastable region is indicated by the smaller size of the phenocrysts, and the labile region was passed so quickly that much of the liquid (at the contact) was quenched to a glass.

The crystallization of a liquid picritic magma could therefore account for the observed size distribution of the olivine crystals, and if crystallization was rapid the diversity of shapes could also be explained.

2. SUMMARY OF PETROGRAPHIC EVIDENCE

Three hypotheseshave been advanced for the origin of the ultrabasic minor intrusions of the Skye region: (1) the intrusion of ultrabasic liquid magmas (Harker 1904, 1909); (2) the intrusion of largely crystalline magmas consisting of olivine crystals lubricated by basaltic liquid (Bowen 1927, 1928); and (3) the intrusion of picritic liquids containing varying proportions of olivine xenocrysts (Drever and Johnston 1958). If the available petrographic evidence from Sills 1 and 1A is tested against these three working hypotheses it is found that the evidence favours the intrusion of a liquid magma.

Evidence considered unfavourable to the hypothesis of intrusion of a basaltic liquid containing a high proportion of olivine crystals is summarized below:-

(1) The fragile appearance of many thin tabular, and skeletal olivine crystals. Bowen (1928) recorded that at the immediate contact of a peridotite dyke in Skye, olivine crystals were bent, fractured and even granulated, but there is no evidence of fracture or granulation of the olivine close to the margins of the Sills 1 and 1A. It is doubtful whether the crystals could have survived rapid transportation from a deep-seated source (section 4) without showing some signs of fracture. Although the crystals would have been well lubricated (40 to 60 per cent of basaltic liquid), mutual interference would have been considerable, and forcible contact of some crystals with the country rock could hardly have been avoided.

(2) The paucity of translation lamellae and undulose extinction in the olivine crystals. According to Turner (1942), such deformational features should be prevalent if a crystal mush were transported and

intruded. Moreover, the features are not restricted to the larger crystals which would presumably constitute the bulk of the previously crystallized olivine, but they occur also in small olivine crystals which are texturally related to the crystallization of the feldspar and pyroxene.

(3) The size distribution of the olivine crystals. Gradation in size from large olivine phenocrysts to the smallest crystals suggests that the growth of all the olivine was controlled by the same conditions. There is little evidence that the olivine crystals grew in two generations.

(4) The marginal variations. The margins of the sills do not correspond to any of the types described by Bowen (1928, p. 150), and there is no evidence that large olivine phenocrysts were trapped in the rapidly chilled liquid at the margins of the sills. Both the mean size of the olivine crystals, and the size and number of very large olivine phenocrysts decreases towards the upper contact of Sill 1. Close to the contact the breadths of crystals at first decrease more rapidly than their lengths (as indicated by the mean elongation ratios in table 5) suggesting that the decrease in mean size is related to specific growth properties of the olivine crystals.

(5) The modal variation of the minerals across the sills. The antipathetic relationship of olivine to pyroxene suggests that the crystallization of these minerals was interdependent. If the pyroxene and feldspar crystallized from an interstitial basaltic liquid the ratio of pyroxene to feldspar should be constant. There is, in fact, a regular variation in this ratio. The olivine ledge of the Palisades is believed to have developed by accumulation of olivine crystals within the sill,

and here the pyroxene/plagioclase ratio is constant above, below and within the olivine-rich zone (Walker, 1940).

(6) The composition of the plagioclase feldspar. The anorthite content of the feldspar is higher than that which is normally found in basaltic rocks (Bowen 1928).

(7) There is good evidence that the temperature of the intruded magma was higher than that of normal basaltic liquids. It is unlikely that a high proportion of olivine would persist in such a liquid without showing some signs of remelting.

The porphyritic texture is the only evidence which could be considered as favourable to the hypothesis, but the size distributions and the habit distributions of the olivine crystals give little indication that the phenocrysts could be considered as a "generation" distinct from the groundmass olivines. It has been shown that crystallization in situ of a picritic liquid would probably produce a similar texture. The hypothesis of intrusion of largely crystalline material derived from basaltic magma does not appear to be tenable for Sills 1 and 1A.

It is possible that about 15 per cent of the picrite consists of olivine phenocrysts unrelated to the main size distribution (Part I). These phenocrysts could have been present in a picritic liquid at the time of its intrusion (Drever and Johnston 1958). Evidence which appears unfavourable to this hypothesis is:-

(1) The decrease in size and number of large olivine phenocrysts from within Sill 1 towards its margin. Drever and Johnston (1958) suggest that similar size gradations from the margins may be the expression of a mechanism of differential intrusion in which a variation in size of olivine xenocrysts was already present. However, the fact that

the breadths of olivine crystals at first decrease more rapidly than their lengths close to the upper contact of Sill 1 (table 5) suggests that the variation in size is related to specific growth properties of the olivine crystals.

(2) No large olivine phenocrysts were found in the chilled margins. All olivine crystals present could have grown essentially in situ. It is probable that the small phenocrysts found in the chilled margins began to crystallize a short distance from their present positions but it is unlikely that they moved far (section 4).

(3) The modal variation of minerals across the sills. The constancy of total olivine plus pyroxene suggests that these minerals grew from the same liquid. If the magma were emplaced as a homogeneous liquid the iron and magnesia content would be fixed at any point within the sills. Crystallization of olivine and pyroxene from the liquid would use up the greater part of the iron and magnesia, and the total olivine plus pyroxene would therefore be approximately constant at any point. The percentages of olivine and of pyroxene vary across the sills. The olivine would take up less silica from the liquid than would the pyroxene, but the high percentage of olivine compared to pyroxene would ensure that the total volumetric percentage of olivine plus pyroxene would not vary greatly on this account. If olivine xenocrysts were present within the liquid before intrusion each xenocryst would represent an initial excess of iron and magnesia over the fixed amount present in the liquid. The xenocrysts would therefore produce an increase in the total olivine plus pyroxene compared to the constant amount which would crystallize from the liquid. The constancy of the total indicates that if xenocrysts were present before intrusion, they were evenly distributed throughout

the sills. But the size distributions of the olivine crystals show that the large phenocrysts near the centre of Sill 1, which represent the possible xenocrysts, decrease in size and number towards the margin of the sill. With such a distribution of xenocrysts the total olivine plus pyroxene should have a maximum value near the centre of the sill. It seems improbable, therefore, that olivine xenocrysts existed in the picrite magma before its intrusion.

Most of the evidence adduced above as unfavourable to the hypotheses involving the intrusion of a partially crystalline magma may be regarded as favourable to the hypothesis of intrusion of a liquid picrite magma. Additional evidence regarded as favourable to this hypothesis is:-

(1) Crystallization of a liquid picrite magma could account for the variations in size and habit of the olivine crystals. The skeletal crystals and parallel growths occur in all sizes and such forms would be expected to grow during the rapid crystallization of a picritic liquid.

(2) The modal variation of minerals across the sills. It was shown above that the crystallization of a liquid magma should produce an approximately constant total of olivine plus pyroxene. Similarly, the regular distribution of alkalis, lime and alumina in a homogeneous liquid should produce an approximately constant proportion of feldspar throughout the sill. The modal measurements indicate that this is so. The modal increase in olivine near the centre of the sills could be accounted for by the slower rate of cooling near the centre, with the result that olivine crystallized alone for a longer period of time than near the margins and was precipitated in excess of its stoichiometric ratio (Bowen 1928). This would leave the remaining liquid depleted in

iron and magnesia with the result that a smaller proportion of pyroxene could crystallize near the centre of the sill than near the margins. Greater heat loss from the tops of the sills than from the bottoms could explain the asymmetry of the olivine and pyroxene variations.

There is no available evidence which may be regarded as definitely unfavourable to the hypothesis of intrusion of a liquid picritic magma, but there are factors which are not completely explained by the hypothesis:-

(1) The margins were not quenched to a glass nor chilled to a uniformly aphanatic rock (Bowen 1928). However, the olivine crystals enclosed by the brown glassy mesostasis of the marginal rocks are much smaller than the olivine crystals elsewhere in the picrite. The delicate skeletal crystals of the margins, two of which are almost as large as the phenocrysts, enclose brown isotropic material identical with the mesostasis surrounding them, and in view of the evidence discussed by Drever and Johnston (1957) it appears possible that the 28 per cent of olivine crystals occurring in the chilled margins could have crystallized essentially in situ. This will be discussed further in section 4.

(2) Although zoning was detected in the olivine crystals, the range of zoning is believed to be small. It seems improbable that 50 to 60 per cent of olivine could crystallize from a liquid magma without significant change in composition but evidence from the system CaO-MgO-FeO-SiO_2 indicates that this is possible (Part III).

(3) The greatest difficulty facing the hypothesis of intrusion of a liquid picrite magma is the high temperature required to keep 50 to 60 per cent of olivine in solution. Evidence from the fusion of the sediment and relevant phase equilibrium studies confirms that the picrite when intruded was hotter than normal basaltic magma, and evidence from

other phase equilibrium studies indicates that picritic liquids can exist at temperatures lower than previously suspected. There is evidence that the sills were emplaced at a high level in the earth's crust, but even if picritic liquids were available at depth, it is difficult to see how they could have reached such a high level without crystallizing.

3. CHEMICAL VARIATION DIAGRAMS

3.1. The FM Percentage

In order to compare the analyzed picrite with the other igneous rocks of the Skye region a chemical variation diagram was constructed (figure 19). Harker (1909), Bowen (1928) and many other petrologists extensively employed variation diagrams in which oxide percentages were plotted against silica percentages, and in such diagrams points representing ultrabasic rocks are characterized by marked scatter from the regular trends usually exhibited by comagmatic rocks ranging in composition from basic to acid. This was adduced by Bowen (1928) as evidence that ultrabasic rocks are crystal accumulates which do not belong to liquid lines of descent. The fact that silica percentage varies only slightly in a wide variety of rock types ranging in composition from ultrabasic to basic tends to invalidate this argument. The silica percentage of a picritic rock could not be considered as a good indication of its degree of differentiation from a hypothetical ultrabasic liquid. The use of silica variation diagrams did not meet with universal approval (Bramall 1933, Krokstrom 1937, Larsen 1938), but for rock series in which the silica percentage varies considerably such diagrams are undoubtedly very useful petrological tools (Bowen 1928). To illustrate the chemical variation in rock series in which silica percentage varies only slightly (e.g. ultrabasic to basic rocks) it is necessary to plot the oxides against a property which does vary. Larsen (1938) remarked that provinces of ultrabasic rocks failed to yield satisfactory curves on any chemical variation with which he was familiar, but plotting the oxide percentages of the Skye rocks against the function

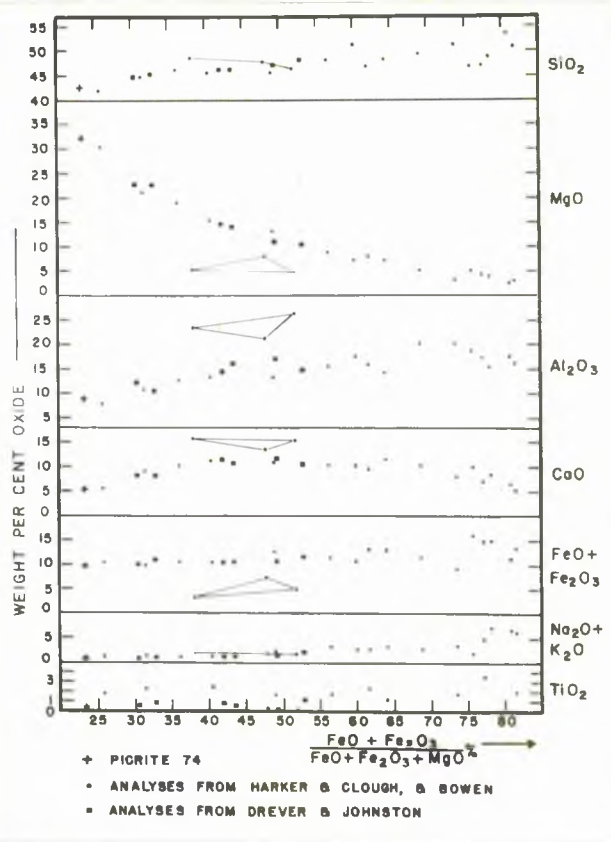


Figure 19. Chemical variation diagram for rocks of the Skye region ranging in composition from ultrabasic to intermediate. The analyses plotted comprise: (1) picrite 74 from Sill 1A, (2) all complete analyses of ultrabasic, basic and intermediate rocks listed by Harker (1904), (3) rocks with peridotitic affinites listed by Bowen (1928, p. 154), and (4) analyses of picritic rocks listed by Drever and Johnston (1958). The analyses illustrate a fairly regular chemical variation, with the exception of the three points connected by lines. These belong to the porphyritic central magma type.

$\frac{(FeO + Fe_2O_3) \times 100}{(FeO + Fe_2O_3 + MgO}$ (the FM Percentage) produces a satisfactory variation diagram, with a wide spread of points between the extremes of ultrabasic and basic compositions. For the basic to acid rocks of the series, the FM percentage varies only slightly, and the use of silica percentage as abcissa would be more successful. The FM percentage was first used

by Wager and Deer (1939) to illustrate the chemical variation in the successive layers of the Skaergaard intrusion, where the silica percentage remains fairly constant. It has since been used successfully by Walker and Poldervaart (1949), and Walker (1953) regards it as a measure of the degree of differentiation of basaltic magma, in which silica tends to remain constant owing to the rough balance between the plagioclase and pyroxene series. The ratio was designated the Mafic Index, M, by Simpson (1954) but the term FM percentage is preferred in the present discussion.

The analyses plotted in figure 19 comprise:- (1) the analyzed picrite in Sill 1A, table 7; (2) all complete analyses of ultrabasic, basic and intermediate rocks listed in the Skye Memoir (Harker 1904); (3) rocks with peridotitic affinities listed by Bowen (1928, p. 154); (4) analyses of picritic rocks listed by Drever and Johnston (1958). Water was omitted and the analyses were recalculated to 100 per cent. With the exception of three gabbros, all points occupy narrow ranges which are bounded in figure 20 by pairs of lines. The exceptions, which are joined together by separate lines, contain unusually high alumina for gabbros, Daly's (1933) average gabbro containing only 17.9 per cent of Al_2O_3 compared to their range of 21 to 26 per cent. They differ also from the trend indicated by the other analyses in their high lime, and low magnesia and iron. According to Harker (1904, p. 104) two of these gabbros contain about 80 and 66 per cent respectively of calcic plagioclase feldspar. They belong to the porphyritic central magma type which Bowen (1928) derived from the plateau magma type by the accumulation of plagioclase crystals. Whatever the origin of these rocks, it is certain that they do not belong to the same line of descent as the olivine

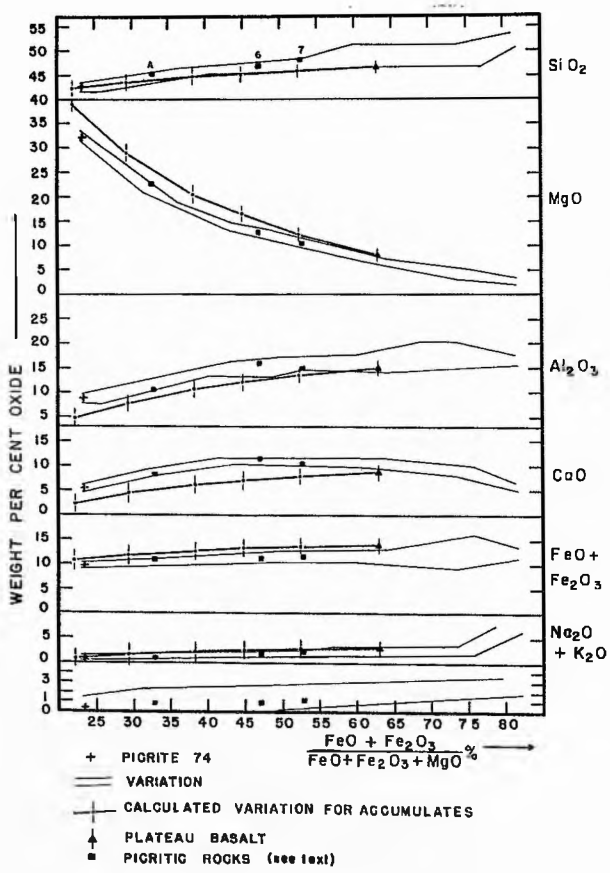


Figure 20. The observed chemical variation for the Skye rocks compared with the variation which would be produced by the accumulation of forsteritic olivine in the plateau basalt of the Hebrides. The pairs of fine lines would enclose the analyses plotted in figure 19 (with the exception of the three which are linked together in figure 19). The heavy line connects the average plateau basalt (Turner and Verhoogen 1951, p. 193) to the calculated compositions of rocks which would be produced by the addition of 10, 20, 30, 50 and 75 per cent of olivine, of composition $Fo_{90}Fa_{10}$, to the average plateau basalt. The points A and 7 represent the analyses of contact facies of picritic rocks of the group, and the point 6 represents the average of non-porphyritic zones in picritic intrusions (Drever and Johnston 1958).

rich rocks, and they will be ignored in subsequent discussion of the chemical variation. FeO and Fe_2O_3 vary irregularly, possibly due in part to the fact that many old analyses are used, but FeO + Fe_2O_3 varies more regularly.

It is believed by the authors of the Mull Memoir (Bailey et alia, 1924) and by Bowen (1928) that the parent magma of the Hebridean province is basalt of the plateau magma type, although this has not been accepted by all petrologists (cf. Tilley 1950, Wager 1956). In figure 20, the observed chemical variation is compared with the calculated variation which would result from the accumulation of forsteritic olivine in the plateau basalt of the Hebrides. According to Drever and Johnston (1958), the average composition of olivine in the picritic rocks of the region is near $Fo_{90}Fa_{10}$. The calculated compositions of the rocks which would be produced by the addition of 10, 20, 30, 50 and 75 weight per cent of olivine (of composition Fa_{10}) to the average plateau basalt (Turner and Verhoogen 1951, p. 193) have been plotted, and the lines through the calculated points, although similar to the observed chemical variation, are higher in magnesia and iron, lower in alumina, and distinctly lower in lime. This difference results from the high anorthite content of the picrites and peridotites.

Other analyses plotted for comparison are the picrite from Sill 1A, and three analyses of picritic rocks given by Drever and Johnston (1958): (A) picritic basalt at 0.5 to 2.5 cms. below the upper contact of a small picritic sill in Applecross; (6) the average composition of fine-grained non-porphyritic zones in picritic intrusions; (7) the upper contact of a small variolitic olivine-basalt sheet from Skye. These analyses will be discussed in section 3.3.

3.2. Chemical Variation within the Quaternary Tetrahedron $CaO-MgO-FeO-SiO_2$.

In Part III, the position of the analyzed picrite of Sill 1A within the tetrahedron representing the system $CaO-MgO-FeO-SiO_2$ was located by projecting its composition on to two joins within the tetrahedron. The joins, $2MgO.SiO_2-2FeO.SiO_2-2CaO.SiO_2$ and $CaO.MgO.SiO_2-FeO-SiO_2$, are approximately at right angles to each other. The positions of the analyses used in the construction of the chemical variation diagrams of figures 19 and 20 may be similarly located and, by projecting the analyses in terms of CaO, MgO, FeO and SiO_2 on to the two joins, the chemical variation of the rocks may be observed in three dimensions (figures 21 and 22). This is a useful supplement to the normal chemical variation diagram already considered. The FM percentage of each rock is recorded alongside its projection in figures 21 and 22, and this permits the identification of each analysis on both projections, because no two rocks plotted have the same FM percentage.

In each projection, the line drawn through the projected points for the Skye rocks illustrates the chemical variation of the rocks with increasing FM percentage, i.e. from ultrabasic to basic rocks. The FM percentage increases fairly regularly, although there are minor reversals in the succession, especially at the basic end of the series. The percentage of normative orthosilicates (allocating all CaO, MgO, and FeO to orthosilicates, see Part III) decreases from ultrabasic to basic rocks and the positions on the projected variation lines corresponding to a value of 50 for the FM percentage coincide with rocks containing 50 per cent of normative orthosilicate. The four oxides CaO, MgO, FeO and SiO_2 comprise a good proportion of the plotted analyses, the percentage ranging from 87 (ultrabasic) to 65 (basic); and the addition of Al_2O_3

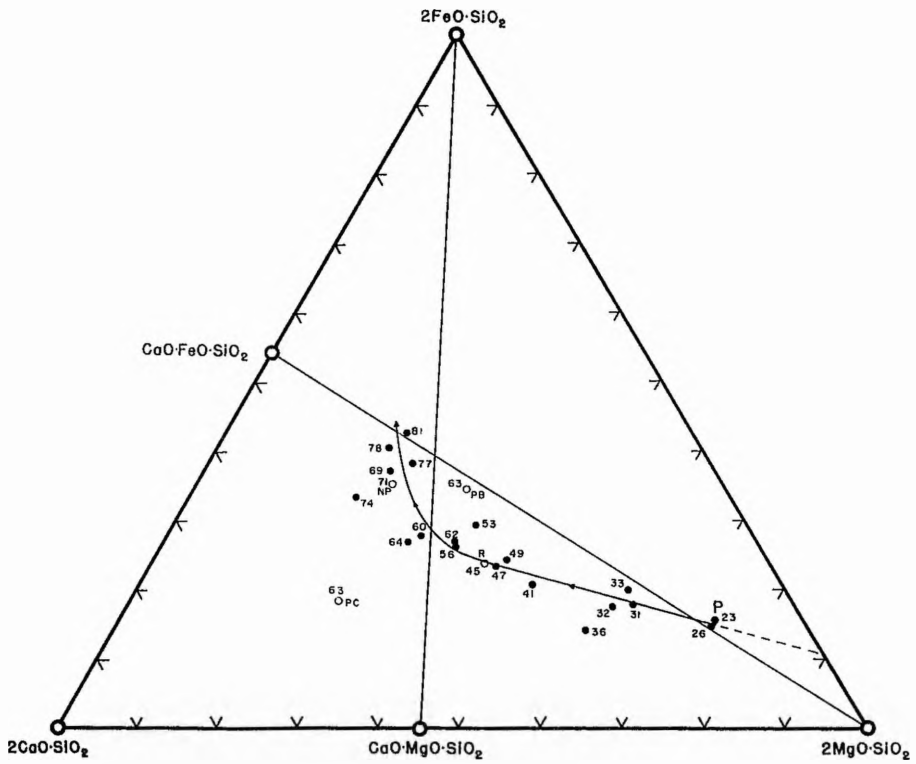


Figure 21. Analyses of ultrabasic to intermediate rocks of the Skye region projected on to the orthosilicate join of the quaternary system CaO-MgO-FeO-SiO_2 (see figure 13). P is the picrite 74 from Sill 1A. Solid circles represent the analyses plotted in figure 19. The open circles are PB, NP and PC:- the average plateau basalt, nonporphyritic central magma-type and porphyritic central magma-type respectively (Turner and Verhoogen 1951, p. 193); R:- the hypothetical parent magma of the Rhum layered intrusion (Brown 1956). The FM percentages of the analyses are given alongside each point which enables the analyses to be located in figures 19 and 22. The line through the points is a projection of the chemical variation of the rocks within the tetrahedron representing the system CaO-MgO-FeO-SiO_2, in the direction of increasing FM percentage. The dotted line is a projection of the variation line extended towards the forsterite-fayalite join.

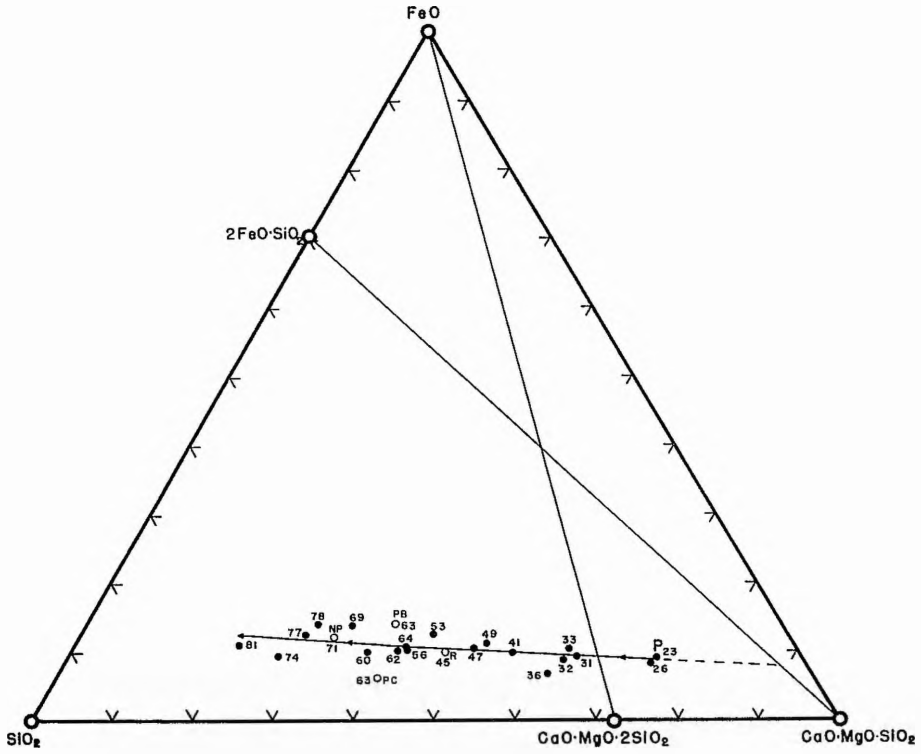


Figure 22. The analyses shown in figure 21 are here projected on to the join $CaO.MgO.SiO_2$-FeO-SiO_2 in the system CaO-MgO-FeO-SiO_2. This join is almost perpendicular to the orthosilicate join, and its intersection with the orthosilicate join is shown by the line $CaO.MgO.SiO_2$-$2FeO.SiO_2$ in figure 21 (see figure 13). The intersection of the orthosilicate join with this figure is shown by the line $CaO.MgO.SiO_2$-$2FeO.SiO_2$. Points, numbers and lines are the same as in figure 21. By considering the projected variation lines in figures 21 and 22, it is clear that the variation line within the tetrahedron is almost linear for FM percentages ranging from 23 to at least 50. The dotted line, within the tetrahedron, must pass very close to the composition $Fo_{90}Fa_{10}$, which is the average composition of olivine in the picritic rocks of the Skye region (Drever and Johnston 1958).

and Fe_2O_3 changes the range from 97 to 86 per cent. Only for the three most siliceous rocks (FM percentages 77, 78, and 81) is the total of the six oxides less than 90 per cent. The Al_2O_3 in the analyses varies regularly from ultrabasic to basic rocks (see figure 19) but the variation of Fe_2O_3 is irregular. Total iron is more regular but FeO, rather than recalculated total iron, was used to plot the points because Fe_2O_3 does not enter the minerals which are quantitatively important in the rocks considered.

If a point lies close to the variation line within the quaternary tetrahedron, its projected points will be close to the projected lines on both joins, figures 21 and 22. A point which is displaced from the line in either projection will be similarly displaced within the tetrahedron. In both projections, the rocks with FM percentages ranging from 23 to 50 (peridotites, picrites and some olivine dolerites) are very close to the variation lines, with the exception of an olivine dolerite with an FM percentage of 36. This rock also contains an unusually high percentage of Fe_2O_3 compared to other rocks with similar FM percentages, and its departure from the variation lines probably results from (1) a faulty analysis, or (2) late oxidation of the rock. There is a somewhat wider spread of points for the more siliceous rocks.

In figure 22, the variation line shows slight but continuous iron enrichment from ultrabasic to basic rocks, and a similar increase in total iron is apparent in figure 19. The marked enrichment in iron shown on the orthosilicate join, figure 21, results from the method of projection. Each projected point was obtained, in effect, by extending the line passing through the SiO_2 corner of the tetrahedron and the point within the tetrahedron until it intersected the olivine join.

The extended lines act as a lever, pivoting on the SiO_2 apex. Rotation of the lever, as the rocks approach the SiO_2 corner with slowly increasing iron, magnifies the iron enrichment on the orthosilicate projection. The more rapid increase in iron content near the basic end of the variation is barely discernible in figure 22, but shows clearly on the orthosilicate join, figure 21.

The spatial arrangement of the variation line within the tetrahedron can be visualized by examining the two projected lines. Extending from the ultrabasic rocks it is almost straight until a more rapid rate of increase in silica towards the basic rocks produces the curvature illustrated in figure 21.

Other analyses plotted for comparison are shown by open circles. They are:- the average plateau basalt (PB), the average nonporphyritic central magma-type (NP), the average porphyritic central magma-type (PC) (Turner and Verhoogen 1951, p. 193), and the hypothetical parent magma (R) of the layered ultrabasic rocks of Rhum (Brown 1956). The average plateau basalt and porphyritic central magma-type are quite far displaced from the variation line while the average nonporphyritic central magma-type and the Rhum parent magma lie very close to the variation line.

3.3. Discussion

Figure 19 demonstrates a regular chemical variation for rocks ranging in composition from peridotites and picrites to dolerites and basalts. This implies that the evolution of these rocks was controlled by similar processes.

Bowen (1928, p. 158) suggested that the ultrabasic minor intrusions were produced by the accumulation in basaltic magma of early precipitates,

principally olivine and plagioclase feldspar. But in his preceding description of several ultrabasic intrusions he stressed the porphyritic character of the olivine and gave little evidence of porphyritic feldspars. On page 157 he wrote: "Occasionally, but by no means frequently, these small dikes contain phenocrysts of basic plagioclase feldspar...." Drever and Johnston (1958) encountered only rare plagioclase phenocrysts in picritic intrusions of the group, and there is no evidence that feldspar phenocrysts were present in the picrite magma of Sills 1 and 1A at the time of intrusion, all feldspar being texturally related to the pyroxene (one small exception is illustrated in plate 7B). That the accumulation of olivine alone is unlikely to have produced the ultrabasic rocks is demonstrated by the difference between the observed chemical variation and the calculated variation curve in figure 20. Similarly, it can be seen from figure 21 that the addition of forsteritic olivine of composition $Fo_{90}Fa_{10}$ to any of the three magma types of the Hebrides (PB, NP or PC) would not produce the observed variation. Of the magma types recognised by the authors of the Mull Memoir (Bailey *et alia*, 1924) only the nonporphyritic central magma type (NP) lies close to the observed chemical variation in figure 21, and the addition of forsteritic olivine to a liquid of this composition would reproduce most closely the observed variation. The hypothetical parent basalt of the layered ultrabasic intrusion in Rhum (1956) lies on the observed chemical variation in figures 21 and 22, but if plotted on the FM diagram, figure 19, it is characterized by lower magnesia and iron, and higher alumina than the Skye rocks with similar FM percentages. The composition of a peridotite from the Rhum intrusion (Brown 1956, Table 9, analysis 1), when plotted in figure 20, corresponds more closely to the calculated

variation than to the observed variation for the Skye rocks, as might be expected from Brown's conclusion that the peridotite was derived by the accumulation of olivine precipitated from the hypothetical parent magma.

As far as the picritic rocks of the Skye region are concerned, there is no evidence for the participation of normal basaltic magma (Drever and Johnston 1958). The petrographic evidence from Sills 1 and 1A favours the hypothesis of intrusion of a liquid magma and it is worthwhile, therefore, to consider the series of rocks which could be produced by the crystallization differentiation of such a magma. The tetrahedron for the quaternary system CaO-MgO-FeO-SiO_2 may be used for this purpose.

The composition of the olivine in the picrite P (figures 21 and 22) is $Fo_{90}Fa_{10}$ (table 1), and the tie line within the tetrahedron connecting P to olivine of this composition would correspond closely, in projection, to the dotted lines shown in figures 21 and 22, which are extensions of the linear portion of the chemical variation. The crystallization of this olivine from the liquid P would cause the liquid to change in composition down a path given by the extension of the tie line passing through P. Such a path would correspond very closely to the observed chemical variation within the tetrahedron for rocks with FM percentages between 23 and 50. The complete or partial separation of liquid from olivine at different stages of crystallization would make available a series of liquids varying in composition from picrites to olivine dolerites. This assumes that the composition of the olivine crystallizing from the liquid does not change in composition as the liquid changes. It was shown in Part III that because of the plateau on the liquidus and solidus surfaces of the orthosilicate join, about 50 per cent of olivine

can crystallize from an ultrabasic liquid without much change in composition during a relatively narrow temperature interval. The chemical variation, when projected on to the orthosilicate join (figure 21), extends across the gently sloping plateau on the liquidus surface (figure 14A) and the tentative conclusions concerning the crystallization of magnesian liquids on the plateau surface are therefore applicable to this series of rocks. It was assumed in Part III that the section $CaO.FeO.SiO_2$-$2MgO.SiO_2$ was a binary system, but in fact the join is not binary nor is the orthosilicate join a ternary system. However, since a plateau persists on the liquidus surfaces of other joins in this and related systems (Part III), the conclusion appears to be valid. All the invariant points within the quaternary system are crowded away from the MgO apex of the tetrahedron into the region near the CaO-FeO-SiO_2 face, on the high silica side of the orthosilicate join (Osborn 1954). Liquidus paths in the system would therefore extend away from the MgO apex of the tetrahedron towards the CaO-FeO-SiO_2 face on the silica side of the orthosilicate join, i.e. in the general direction indicated by the observed chemical variation.

Assuming that the observed chemical variation does represent a liquid line of descent, the chemical variation line may then be regarded as a possible liquidus path. The composition of the olivine in equilibrium with any liquid is given by a tie line tangent to the liquidus path passing through the liquid composition. The composition of the olivine in equilibrium with any liquid on the linear part of the chemical variation line is therefore given approximately by the intersection of the dotted line with the join forsterite-fayalite. This is close to $Fo_{90}Fa_{10}$, which is the average composition of the olivines found in these

rocks (Drever and Johnston 1958). Solid solution of $2CaO.SiO_2$ in the olivine would occur in the synthetic system, but the amount of solid solution would be small (this can be seen by transferring the dotted line in figure 21 to the 1600°C liquidus and solidus isotherms in figure 14A), and it is ignored in the present discussion. The curvature of the projected line in figure 21 could result from the later crystallization of calcic plagioclase and pyroxene in addition to, or instead of, olivine.

Experimental determination of liquidus paths and tie lines in the quaternary system is required before definite conclusions can be made, but it seems possible, from the available information, to account for the observed variation of the Skye rocks by the fractional crystallization of an ultrabasic liquid. Similarly, the observed variation could be explained by the fractional melting of crystalline peridotite.

Four widely spaced analyses plotted in figure 20 represent possible liquids. They comprise the picrite 74 from Sill 1A (table 7) and three analyses given by Drever and Johnston (1958). The analysis 6 is the average of a non-porphyritic facies of picritic intrusions which is believed to represent a eucritic liquid. Analyses 7 and A are quickly cooled, fine-grained marginal facies of two picritic sills, which may represent original liquids, although both marginal rocks contain small olivine phenocrysts.

It is apparent that more information is available from the chemical variation plotted in the tetrahedron $CaO-MgO-FeO-SiO_2$ than from the conventional two dimensional variation diagram. This is because the crystallization of minerals from a magma involves the variation of several oxides at the same time, and the extra dimension provided by the

tetrahedron shows more clearly the behaviour of each oxide represented, in relation to the other oxides. The fact that the plateau basalt and the porphyritic central magma-type are not directly related to the observed chemical variation is obvious from figures 21 and 22, but this fact would not be clear from figure 20.

The immediate concern of this section is to examine the chemical variation of the non-alkaline picritic rocks of the Skye region, but Drever and Johnston (1958) described in addition a group of alkaline picritic intrusions to the north of this group (area II, figure 1). The two groups are almost completely separated in space (and possibly in time). The use of the three dimensional system of plotting chemical variation diagrams may provide a means of differentiating between the two series of rocks. Supplementary diagrams could be constructed within the tetrahedra CaO-MgO-Al_2O_3-SiO_2 and CaO-FeO-Al_2O_3-SiO_2, although these would probably yield less information for picritic rocks because Al_2O_3 would not be expected to vary greatly until plagioclase became a dominant constituent of the rocks.

For rocks more acid than basalt, the importance of alkalis is such that they cannot be neglected in chemical variation diagrams. Suitable tetrahedra for the examination of basalts and intermediate rocks might be those with corners representing CaO, $FeO + MgO$, $Na_2O + K_2O$, Al_2O_3 and SiO_2. An alternative method would be to plot the recalculated normative minerals such as anorthite, albite, nepheline, diopside, hypersthene and quartz. Barth (1936) used a tetrahedron with corners representing normative diopside, hypersthene, albite and anorthite in his derivation of the "f(norm)" for basaltic rocks, and in his discussion of the production of oversaturated or undersaturated residual melts through the

fractional crystallization of basaltic magmas the qualitative use of a tetrahedron with corners representing olivine + diopside, anorthite, nepheline and silica was very effective.

The separation of the plateau basalt and the nonporphyritic central magma type in figures 21 and 22 suggests that this system of plotting may permit a distinction between tholeiitic and alkaline basaltic rocks. It would be interesting to establish, by plotting a large number of analyses, whether alkaline and non-alkaline ultrabasic rocks can be related directly to the alkaline and tholeiitic type basalts, respectively. If this proved to be the case, it would be of considerable interest in relation to current hypotheses in petrogenesis, particularly to the hypothesis that primitive basalts are derived from the peridotite substratum (section 4). Tilley (1950) recognized that the distinction between tholeiitic and alkaline rocks does not depend upon the presence or absence of olivine, as suggested by Kennedy (1933), but depends upon the degree of silica saturation of a rock.

4. THE SOURCE AND NATURE OF PICRITIC MAGMAS

From the available evidence it may be tentatively concluded that Sills 1 and 1A were emplaced essentially as liquid magmas. The chemical variation diagrams imply that picritic intrusions of the whole group have a common parentage, and the most probable parent is ultrabasic material, because it appears from the petrographic and chemical evidence that normal basaltic magma was not involved in the development and intrusion of the picrites.

Harker (1909) and Vogt (1923, 1924) pointed out the difficulties involved in the derivation of ultrabasic rocks from basalts by a process of gravitative accumulation but, since the hypothesis became so widely accepted, there has been a tendency to overlook these difficulties. In order to account for the high forsterite content of olivine and the high concentration of Cr_2O_3 typical of ultrabasic rocks both Harker and Vogt concluded that it would be necessary for crystallization and refusion to occur repeatedly in intercrustal reservoirs. After a detailed mineralogical and chemical study of dunites and of olivine nodules from basalts, Ross *et alia* (1954) also concluded that the high chromian content of the spinels and pyroxenes seemed to be an improbable concentration from basaltic magma. Brown (1956) accounted for the development of great thicknesses of peridotite and allivalite in the layered intrusion of Rhum by the gravitative settling of crystals in a magma chamber from which basalt was intermittently extruded, and replenished from below. Such a process would permit the concentration of Cr_2O_3 and the accumulation of large quantities of forsteritic olivine without repeated crystallization and fusion, but the hypothesis is not applicable to the picritic minor intrusions. The selective fusion of peridotites accumulated in

local reservoirs by this mechanism could give rise to a series of picritic magmas but this is believed to be unlikely for the following reasons: (1) The analyzed peridotite and the hypothetical parent magma for the Rhum intrusion depart somewhat from the observed chemical variation within the picrite group (section 3.3). (2) The Rhum peridotites alternate with layers of allivalite and if picritic magmas were developed allivalitic magmas should be simultaneously developed. There is no series of allivalite intrusions comparable to the picrite intrusions. (3) The picrites are distributed over a wide area (figure 1) and were probably derived from a source more widespread than local magma chambers. (4) If Sills 1 and 1A were emplaced as liquids, the high temperature required suggests that they were developed at depth. Drever and Johnston (1958) tentatively proposed that the picrites were produced by selective fusion of the peridotite layer of the earth's crust, and this appears to the writer to be the most likely source of ultrabasic material.

Bowen (1928) regarded the peridotite substratum as the source of basaltic magmas and Hess (1938) suggested that primary peridotite magmas could be derived from the same layer. The concept of primary or parent basalts derived from world wide layers of glassy or crystalline basalt (e.g. Daly 1933, Kennedy and Anderson 1938) played an important role in the evolution of petrological theory, but such basalts are not always adequate to explain the succession of differentiates produced in a given area. Kuno (1937) suggested that the primitive basalts are themselves differentiates of a more basic magma, e.g. eucrite, and Frankel (1942) found it necessary to invoke the existence of a substratum more basic than the Karroo magma to explain the presence of certain thin dykes associated with the Karroo intrusions. It therefore seems preferable

to describe the basaltic magma types which are of world wide distribution as primitive, rather than primary or parental basalts. In several recent publications there have been renewed suggestions that primitive basaltic magmas are derived by the selective fusion of the peridotite substratum (Hurley 1951, Green and Poldervaart 1955, Powers 1955, Wager 1956), and the available geophysical evidence appears to be compatible with the suggestion (Hurley 1951, Powers 1955). Ross et alia (1954) concluded that most dunites and olivine-rich nodules in basalts were derived from the peridotite substratum, and suggested that the basalts enclosing the nodules were also derived from the deep-seated peridotite.

Since, in the opinion of these writers, the selective fusion of peridotite gives rise to basaltic liquids only, there appears to be a limit to the amount of heat available, such that the temperature of the magma generated does not exceed a definite value (Powers 1955). But because the primitive basalts range in composition from saturated tholeiitic types to undersilicated alkaline types (Green and Poldervaart 1955) there must be a range of temperatures and compositions (and other unknown factors) involved in the process of selective fusion. If Sills 1 and 1A were emplaced as picritic liquids, and if the liquid were derived from the peridotite substratum, as suggested above, it would be unreasonable to assume that this was an isolated occurrence. If the partial fusion of a primary peridotite layer is admitted as a source of basaltic magmas, it is probable that liquids ranging in composition from basalt to picrite become available in depth at rare intervals.

The composition of a liquid produced by selective fusion of peridotite will depend mainly upon three factors: (1) the composition of the solid peridotite, (2) the temperature of fusion, and (3) the shape of

the liquidus surface in the complex system represented by the peridotite. The third factor may be of critical importance. For instance, if the liquidus surface were fairly steep near basaltic compositions an increase in the temperature would produce little variation in the composition of the liquid basalt available for eruption. On the other hand, if the plateau feature on the orthosilicate join of the system $CaO-MgO-FeO-SiO_2$ (Part III) persists in the complex peridotite system, a relatively slight increase in the amount of heat available once the temperature of the basaltic melt had passed a certain value would cause the melting of a high proportion of olivine, producing liquids of picritic composition. In migrating to higher levels of the earth's crust, the liquids developed could carry with them inclusions of olivine, spinel or masses of partially melted peridotite, which could recrystallize during uprise and crystallization of the magma to form cognate inclusions of peridotite. A process of selective fusion of the peridotite substratum could therefore give rise to a wide variety of products at depth:-

(1) Basaltic liquid fraction.

(2) Picritic liquid fraction.

(3) Peridotitic liquid.

(4) Liquids ranging in composition from basalt to picrite, containing varying proportions of olivine and spinel xenocrysts, and perhaps inclusions of peridotite or dunite (see 5).

(5) A residue of dunitic composition, with some interstitial liquid.

These products would become even more diversified when they were intruded to higher levels in the earth's crust. The tentative conclusion that Sills 1 and 1A were emplaced as liquids suggests that under favourable conditions an ultrabasic liquid could reach high levels, but this

must be considered as a rare occurrence. Drever and Johnston (1958) recognized a recurrent pattern of variation in the picrite intrusions of the group which they tentatively regarded as the expression of an earlier differentiation during the selective fusion of ultrabasic material, involving the partial separation of liquid from the solid fraction. In addition, there appears to be a range of temperatures involved in the intrusion of the picritic material, Sills 1 and 1A being exceptional in their high temperature.

High temperatures would be required for the development of an ultrabasic liquid, and if such a liquid were intruded slowly, it would certainly begin to crystallize before it reached a high level in the earth's crust. It is possible that such a magma would be almost completely crystallized by the time it came to rest, in which case it would be emplaced as a mush of olivine crystals lubricated by a residuum of basaltic liquid. This could account for the features described by Bowen (1928, p. 150) at the margins of many peridotite intrusions. Crystallization of olivine during the slow uprise of a picritic liquid could also result in a process of filtration, whereby the early precipitated olivine crystals could be left behind while a liquid residuum of basaltic composition could continue to higher levels, perhaps followed more slowly by the largely crystalline magma. This is essentially the same mechanism of intrusion proposed by Bowen (1928), but here is an alternative source for the basaltic liquid and crystalline material. Bowen (1928) observed vertical variation in the amount of olivine occurring in some peridotite dykes in the Cuillins, and a ready explanation is found if such a process of filtration occurred during the slow uprise and crystallization of picritic liquids.

A process of selective fusion of deep-seated peridotite could thus lead to the intrusion of picrite magmas occupying a wide range of composition and physical state, which would depend upon: (1) conditions during fusion, (2) the effectiveness with which the liquid fraction was separated from the unmelted peridotite, and (3) the rate of intrusion, which would control the amount of olivine crystallizing during uprise of the magma. The proposed mechanism of generation and intrusion of picritic magmas is apparently compatible with the field and petrographic evidence described by Bowen (1928), whereas the hypothesis of Bowen (1928) is unable to account for many of the observed petrographic features of Sills 1 and 1A, or for the variations occurring within the group of picritic intrusions as a whole (Drever and Johnston 1958).

It is difficult to see how the picrite of Sills 1 and 1A could have reached a high level in the earth's crust as a liquid magma. Intrusion must have been extremely rapid and the influence of volatiles dissolved in the original liquid may be important. The high concentration of H_2O and P_2O_5 in the fused xenolith (table 10) proves that volatiles were available during metamorphism, and it was concluded in Part II that they were derived from the picrite rather than from the sediment. The percentage of volatiles present in the peridotite substratum must be very small, but the local development of liquid by fusion would probably result in the concentration of available volatiles in the liquid phase (Hess 1938). (Powers (1955) concluded that the early basalts produced by the selective fusion of the peridotite layer in the Pacific were rich in volatile materials). The widespread fusion developed below Sill 1A suggests that the picrite magma contained a high proportion of volatiles when intruded. That the volatile components were lost from the picrite

during consolidation is confirmed by the absence of serpentine in most of the olivine crystals and by the chemical analysis of the picrite (table 7). Original volatile materials retained by the rapidly chilled margins may be responsible for the complete serpentinization of the olivine crystals in the chilled margins. The degree of fusion varies even near Sill 1A which suggests either that the volatiles in the picrite were initially localized or that the volatiles became concentrated in favourable localities after intrusion. A picritic liquid would be extremely fluid when intruded because of its high magnesia content. It therefore seems improbable that the volatiles could have been concentrated locally prior to intrusion, but they would have been able to migrate freely after intrusion in response to the changed conditions. During uprise of a liquid picritic magma, the confining pressure would decrease and the volatiles would be free to escape, but the high concentration of volatiles in the fused sediment near Sill 1A suggests that intrusion was sufficiently rapid, and the walls of the conduit through which the magma arose sufficiently impervious to retain the volatile material within the magma. Fusion in connection with the other picrite intrusions of the group is rare, and this may be accounted for in part by the gradual escape of volatiles from the magmas during their uprise.

Only when some weakness existed in the country rocks would the volatiles be able to escape from the magmas, and it is possible that the decomposition of muscovite in the sediments near Sill 1A provided the first avenue of escape for the volatiles by forming passageways between the constituent grains of the sediment. The concentration of volatiles near the escape routes would lower the effective liquidus temperature of the picrite in these regions and would permit slower crystallization

of the final liquid residuum. On the other hand, this would result in depletion of the volatile components elsewhere in the magma, with an effective increase of liquidus temperatures and a rapid crystallization of the magma. This could account for the larger size of the feldspar and pyroxene crystals in Sill 1A than in Sill 1 (plates 4 to 6).

A picritic liquid could only be expected to reach a high level in the earth's crust before beginning to crystallize if it were intruded rapidly, and if it retained its volatile components during intrusion. As soon as the volatiles were able to escape, the effective liquidus temperature would be raised and rapid crystallization of olivine would follow (as indicated by the plateau feature on the orthosilicate join of the system CaO-MgO-FeO-SiO_2). Bowen (1928) considered that the absence of ultrabasic effusives was strong evidence that ultrabasic magmas never existed as liquids, but Vogt (1923) maintained that such liquids would be so hot, that they would crystallize before reaching the surface. The role of volatiles seems to be as important as that of temperature, however, because it is extremely unlikely that an ultrabasic liquid could retain its volatiles until it were extruded as a lava (Hess 1938).

Although it has been concluded that most of the observed petrographic features of Sills 1 and 1A could be accounted for by the crystallization *in situ* of a liquid picrite magma, it would be unrealistic to assume that crystallization did not commence before the magma had come to rest in its present position. However, crystallization *in situ* need not refer to crystallization in a static magma, but could refer also to crystallization in a moving magma, provided that there was no differential movement between crystals and liquid. The rapid intrusion necessary for the picritic liquid to reach its high level in the earth's crust means that

the process of intrusion was dynamic and, if crystallization began before the magma came to rest, it is probable that the crystals already precipitated were carried along with the liquid. The parallel arrangement of some olivine tablets near the margin of Sill 1 suggests that movement did not cease when the magma reached its present position, but the apparently random arrangement of elongated olivines in the central parts of the sills suggests that movement did not continue for long after the magma began to crystallize. If crystalline phases were present in the liquid at the time of its emplacement they should be represented within the rapidly chilled margins. No large crystals were found in the chilled selvages examined, and it was concluded that all of the olivine present could have crystallized in situ. However, some of the larger crystals in the selvages could represent crystals which began to grow before they reached their present positions. The tendency for some larger crystals to lie close to the contact with the sediments suggests that this might be the case. Their small size relative to the olivine crystals a short distance from the contact suggests that they did not begin to crystallize far from their present position.

It is possible, therefore, that crystallization commenced when the rapidly flowing liquid magma was approaching the upper levels of the crust. By the time the magma was emplaced, it may have contained a sprinkling of olivine crystals about the size of the largest crystals enclosed by the brown glass of the chilled selvages, and those which were not trapped in the selvage continued to grow after the magma came to rest. A detailed examination of the marginal facies of both sills is required before more definite conclusions can be reached. It seems reasonably certain from the summary of petrographic evidence (section 2) that differential movement between liquid and crystals did not occur.

CONCLUSION

It was stated in the Introduction that the research completed on Sills 1 and 1A constitutes an integral part of the larger field of research on picritic rocks under the direction of Dr. H. I. Drever. One of the aims of this research is to test the adequacy of the hypothesis of olivine accumulation to account for the origin of all olivine rich igneous rocks. The available evidence favours the hypothesis that the picrite of Sills 1 and 1A was emplaced essentially as a liquid magma, possibly derived by the partial fusion of the peridotite substratum. Other picritic intrusions of the group probably originated similarly, but there is evidence that they were emplaced in a variety of physical conditions. It is tentatively concluded that the diversity of the magmas was controlled mainly by:

(1) The conditions at depth attending the fusion.

(2) The mechanics of intrusion.

(3) The proportion of volatiles retained by the magmas as they approached high levels.

The hypothesis of olivine accumulation appears to be inadequate to explain the origin of either Sills 1 and 1A or the other picritic intrusions of the Skye region.

There is much evidence proving that accumulation of olivine crystals can and does occur during the process of crystallization of basaltic magma, but this does not mean that olivine rich and ultrabasic rocks may not be derived from other sources, and by other processes. Although gravitative accumulation of crystals may be the dominant process in magmatic evolution it is not the only one, and in view of the complexity

of magmas and magmatic processes it appears unjustifiable to erect a single hypothesis for the origin of all picritic and ultrabasic rocks in their many and varied occurrences. Turner and Verhoogen (1951) stressed the fact that there are several evolutionary processes active in petrogenesis and concluded that the only concrete evidence is offered by the rocks themselves. The need for a more critical approach to the theory of olivine accumulation, as advocated by Drever (1952), is now substantiated by several examples of which the most thoroughly documented is the series of picritic rocks of the Skye region. It is significant that much of the evidence on which Bowen (1928) based his arguments in support of olivine accumulation in basaltic magmas was drawn from this series of intrusions which have proved to be incompatible with the hypothesis after further detailed study.

This emphasizes a truism which is well known to petrologists, but which is easily forgotten; namely, that however firmly entrenched a petrological theory may become it can never be more than a working hypothesis which requires modification as more evidence becomes available.

APPENDIX

DISCREPANCIES BETWEEN OPTIC AXIAL ANGLES OF OLIVINE CRYSTALS MEASURED OVER DIFFERENT BISECTRICES

Introduction

The measurements recorded below were made in order to compare the results obtained by single axis measurements with the results obtained by double axis measurements over α and γ.

Game (1941) measured the refractive indices and optic axial angles of olivine crystals from west Greenland and reported that:

> "a set of values obtained about one bisectrix usually show fair mutual agreement but differ by as much as 7^{o} or 8^{o} from another set obtained about the other bisectrix (single axis measurements) whereas the mean of the two sets shows good agreement with the value inferred from the measurement of β ...." "....no explanation can be offered."

Frankel (1942), in studies of the olivines of Karroo dolerites, found that the sets of single axis 2V measurements made about α and γ varied as much as 7^{o} from each other and that the mean value of each set did not show good agreement from the value suggested from measurement of β. The mean of approximately the same number of single axis measurements taken about both α and γ was in good agreement with double axis measurements and the value obtained from β. He referred to the results of Game and concluded that the two studies demonstrated that single axis 2V measurements may be quite unreliable. Johnston (1953), in a study of the olivines of the Garbh Eilean sill, used the more accurate conoscopic method of Hallimond (1950) and, whenever possible, confined his observations to double axis measurements. This ensured a higher degree of accuracy than is possible with the orthoscopic method. He found that the measurement of $2V_{\alpha}$ was consistently smaller than $2V_{\gamma}$,

the average difference being 2.4°. The average of an approximately equal number of determinations about each bisectrix was taken as the true 2V of the olivines in the rocks. The existence of a difference between sets of double axis measurements using the more precise conoscopic method suggests that the difference noted by Game and Frankel cannot be attributed solely to the inaccuracy of single axis measurements. Wilkinson (1956) made optical determinations of the olivines from a teschenite sill. Double axis determinations were made always across the acute bisectrix, but the presence of magnesian olivine with large optic axial angles involving high angles of rotation around A_4 discouraged such determinations and in the majority of cases the optic axial angle was determined by single axis methods. Agreement was "moderately good" between the mean values of double axis and single axis measurements, and "good correspondence" was found in compositions inferred from refractive indices and optic axial angles. No comparison was possible between double axis measurements about α and γ, and no discrepancy was found between single axis measurements made over α and γ. Therefore the results and conclusions of previous workers are contradictory.

Methods and Measurements

There appears to be no general agreement concerning the use of the terms "direct" and "indirect" as applied to the measurement of optic axial angles. Measurements made about one axis are frequently referred to as "indirect" but the writer follows Fairbairn and Podolsky (1951) in describing both single and double axis measurements as direct methods. Indirect methods then include extinction angle procedures and relative

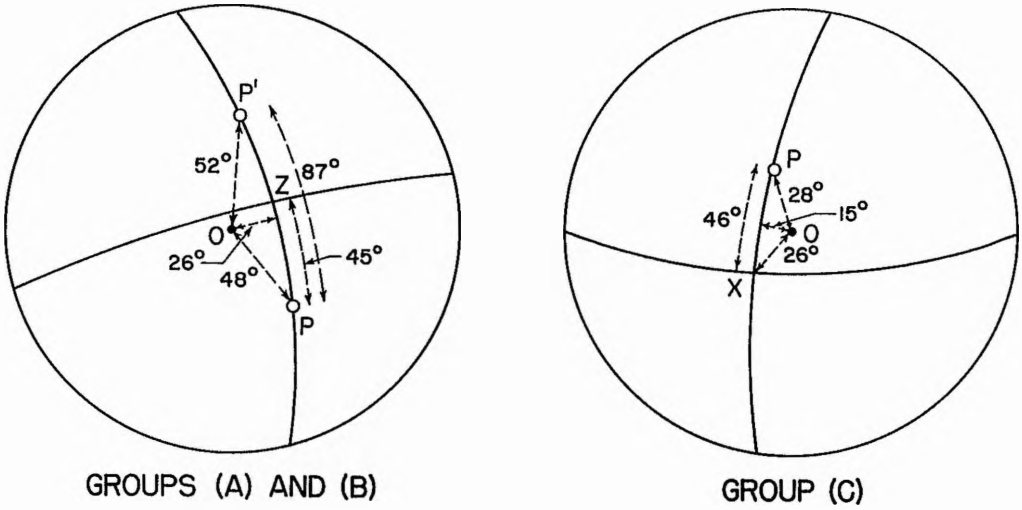


Figure 23. Stereographic projections of olivine crystals illustrating the measurement of 2H by the three methods (A), (B) and (C).
a. Crystal 50a in table 13. For method (A), $2H = PP' = 87^{o}$. For method (B), $2H = 2PZ = 90^{o}$.
b. Crystal 50i in table 13. Method (C), $2H = 2PX = 92^{o}$.

retardation methods. Techniques used were as follows:-

(A) On suitably orientated grains direct double axis determinations were made using the conoscopic method. In addition, stereographic projections of optical data were completed for each crystal, the orthoscopic method being used to locate the bisectrix (figure 23a).

(B) Using the stereograms constructed in (A), direct single axis determinations were also made on these crystals. The angle between the bisectrix and the optic axis making the smaller radial angle with the centre of the projection was doubled to give 2H (figure 23a).

(C) On grains not suitably orientated for double axis measurements direct single axis determinations were made using the stereographic projection (figure 23B). Optic axes were located by the conoscopic method.

TABLE 13. MEASUREMENT OF OLIVINES IN SILL 1

SPEC.		TILT of OAP.	2H						(-)2V			
			DOUBLE AXIS			SINGLE AXIS			2-AXIS		1-AXIS	
			OP'	α	γ	OP	α	γ	α	γ	α	γ
50	a	26	52		87	48		90		94		91
	b	24	52		86	44		86		95		95
	c	10	48		87.5	40		88		93.5		93
	d	21				38		88				93
	e	19				34		90				91
	f	23				33	92				91	
	g	16				30	93				92	
	h	10				30	91				90	
	i	15				28	92				91	
48	a	34	54		85	50		88		96		93
	b	30	54		86	47		86		95		95
	c	20	52	93		47	95		92		94	
	d	4	51.5		85	34		88		96		93
	e	2	45		87	42		87		94		94
	f	4	44.5		87.5	43		88		93.5		93
47	a	5.5	53	93		40	93		92		92	
	b	7	49	93		44	91		92		90	
	c	22.5				32		90				91
	d	5				24		90				91
	e	2				24	90				89	
46	a	7.5	56	92.5		37	92		91.5		91	
	b	10	54	92		38	95		91		94	
	c	11	53		88.5	38		89		92.5		92
	d	4	48	93.5		45.5	95		92.5		94	
	e	13				35		89				92
	f	5				26	93				92	
45	a	22.5	54	92		39	92		91		91	
	b	12	54	92.5		40	93		91.5		92	
	c	27	53	92		49	91		91		90	
	d	15.5	52		86	39		87		95		94
	e	25				38	92				91	
	f	20				32		86				95
	g	19				32		90				91
	h	14				32		88				93
	i	0.5				31.5	94				93	
	j	7				28		88				93
	k	4.5				24		86				95

OAP: optic axial plane. OP' and OP: the radial angles occurring in each measurement.

TABLE 14. MEASUREMENT OF OLIVINES IN SILL 1A

SPEC	TILT of OAP.	2H						(-)2V			
		DOUBLE AXIS			SINGLE AXIS			2-AXIS		1-AXIS	
		OP'	α	γ	OP	α	γ	α	γ	α	γ
73 a	4	55	90		35	92		89		91	
b	13.5	53	93		43	94		92		93	
c	5	53	92		43	92		91		91	
d	5	52	91.5		40	92		90.5		91	
e	2	52		90	39		92		91		89
f	10	51	92		43	94		91		93	
g	28.5				37	90				89	
h	2.5				28.5		87				94
i	10				28	93				92	
j	4				23		90				91
74 a	11	54	91.5		40	92		90.5		91	
b	13	53	92		39	92		91		91	
c	19	53	91.5		44	90		90.5		89	
d	26	50		87.5	48		89		93.5		92
e	0.5	48.5		88.5	40		88		92.5		93
f	12	48		88	43		88		93		93
g	8				26	91				90	
h	1				27		88				93
75 a	2	53.5	91.5		38	94		90.5		93	
b	22	52.5		88	44		89		93		92
c	15	52	91		42.5	92		90		91	
d	4.5	51	91		40	92		90		91	
e	12	51		88	39		90		93		91
f	17.5	49		89.5	45		90.5		91.5		90.5
g	14.5				36	95				94	
h	20.5				35	93				92	
i	5				33		92				89

OAP: the optic axial plane. OP and OP': the radial angles occurring in a given measurement.

The measurements, made on sixty-four crystals in eight specimens from Sills 1 and 1A are listed in tables 13 and 14. Two or three thin sections were used from each specimen. Two examples will illustrate the form of tabulation. Figure 23a is the stereogram for crystal 50a in table 13. The tilt of the optic axial plane (OAP) is 26°. In the double axis measurement (group A), $OP' = 52^{\circ}$ is the greatest radial angle measured and $PP' = 87^{\circ}$ is the value of $2H_{\gamma}$. In the single axis measurement (group B) OP is the greatest radial angle measured and $PZ = 45^{\circ}$ is the value of H_{γ}, giving $2H_{\gamma} = 90^{\circ}$. OP is always less than OP' so that the single axis measurements involve smaller angles of tilt of the universal stage than do the double axis measurements. Figure 23b is the stereogram for crystal 50i in table 13 (group C). The tilt of the optic axial plane (OAP) is 15°. OP is the greatest radial angle measured and $PX = 46^{\circ}$ is the value of H_{α}, giving $2H_{\alpha} = 92^{\circ}$.

Values of 2H were converted to 2V using the refractive index of the hemispheres (n) and the refractive index β of the olivines. In group (A), the radial angles measured from the centres of the projections to the optic axes were corrected, and 2V was then measured on the great circle passing through the two corrected points (Emmons 1943). By this method 2V was obtained from 2H with an accuracy of $\pm 0.5^{\circ}$. Conversion of H directly using the correction $\sin V = \frac{n.\sin H}{\beta}$ was found to give the same result for 2V within $\pm 0.5^{\circ}$. Therefore the simple conversion of H to V was used in groups (B) and (C). The converted value of $2H_{\alpha}$ gives $(-)2V_{\alpha}$ and the converted value of $2H_{\gamma}$ gives $(+)2V_{\gamma}$. For comparative purposes the supplement of $(+)2V_{\gamma}$ is listed as $(-)2V_{\gamma}$. Thus, in tables 13 and 14, values of (-)2V are listed in four columns for determinations about α and γ by both single and double axis methods.

Angles of tilt of the universal stage were kept as small as possible. In the double axis measurements the tilt of the optic axial plane was generally less than 25^{o} and the greatest angle of tilt was 34^{o}. The greatest radial angle involved in a measurement, however, usually exceeded 50^{o}, whereas in the single axis measurements for the same grains the greatest radial angle, with one exception, was always less than 50^{o}. The significance of this fact will be discussed below. In the single axis measurements of group (C) 38^{o} was the greatest tilt of the stage, but most angles were less than 25^{o}.

The accuracy of the measurements varies with the method employed. In group (A) the optic axes may be located with an accuracy of $\pm 0.25^{o}$ by the conoscopic method (Hallimond 1950) giving a possible error of $\pm 0.5^{o}$ for 2H in a given crystal. In groups (B) and (C) the optic axes may be located with an accuracy of $\pm 0.25^{o}$ and the second optic symmetry plane, containing the optic normal, can be found to within $\pm 1^{o}$, using the orthoscopic method. Hallimond (1950) and Turner (1942a) state that the accuracy of measurements is variable for different directions within the indicatrix, and some planes were found which appeared to give complete extinction through a range of 4^{o} of tilt, i.e. $\pm 2^{o}$ accuracy. The mean of several readings for such planes was taken, and the maximum error for the determination was probably reduced to $\pm 1^{o}$. The estimated maximum error for 2H of a given grain by this method is therefore $\pm 2.5^{o}$. These experimental errors will be increased slightly by the index corrections.

Table 15 compares the values of (-)2V obtained about α and γ for the three groups of measurements. The arithmetic means of (-)2V and the standard deviation of the mean for each column have been calculated.

TABLE 15. COMPARISON OF (-)2V OBTAINED BY DIFFERENT METHODS

(A) Double axis measurements. (B) Single axis measurements for same grains as in (A). (C) Single axis measurements with no radial angles greater than 40°.

	SILL 1						SILL 1A					
	(A)		(B)		(C)		(A)		(B)		(C)	
	α	γ	α	γ	α	γ	α	γ	α	γ	α	γ
	94		91		91	93	89		91		91	89
	95		95		92	93	92		93		91	94
	93.5		93		90	91	91		91		89	91
					91		90.5		91		92	
	96		93			93	91		93			
	95		95					91		89		
	96		93				90.5		91		91	93
	94		94				91		91		91	93
	93.5		93				90.5		89		90	
92		94						93.5		92		
92		92			92	91		92.5		93		
92		90			89	91		93		93		
91.5		91			91	92	90.5		93		93	91
91		94			94	92	90		91		91	89
92.5		94			92		90		91		94	
	92.5		92					93		92	92	
91		91			91	94		93		91		
91.5		92			92	95		91.5		90.5		
91		90			91	91						
	95		94		93	93						
						93						
						95						
$\bar{x}$	91.6	94.5	92	93.3	91.5	92.6	90.5	92.5	91.4	91.5	91.4	91.4
2.6 x s	0.5	0.9	1.4	0.9	0.9	1.0	0.6	0.9	0.9	1.4	1.0	2.0
Av.	93.0		92.7		92.1		91.5		91.5		91.4	

$\bar{x}$ Arithmetic mean; s Standard deviation of the mean; Av. Average of the means of (-)2V obtained by measurements over α and γ.

With 99 per cent certainty, the true value of (-)2V lies within the range arithmetic mean ± 2.6 x standard deviation of the mean, and this may be accepted with confidence as the maximum error of the means. The values of 2.6 x standard deviation, listed in table 15, are very close in magnitude to the estimated experimental errors for single measurements.

Discussion of Results

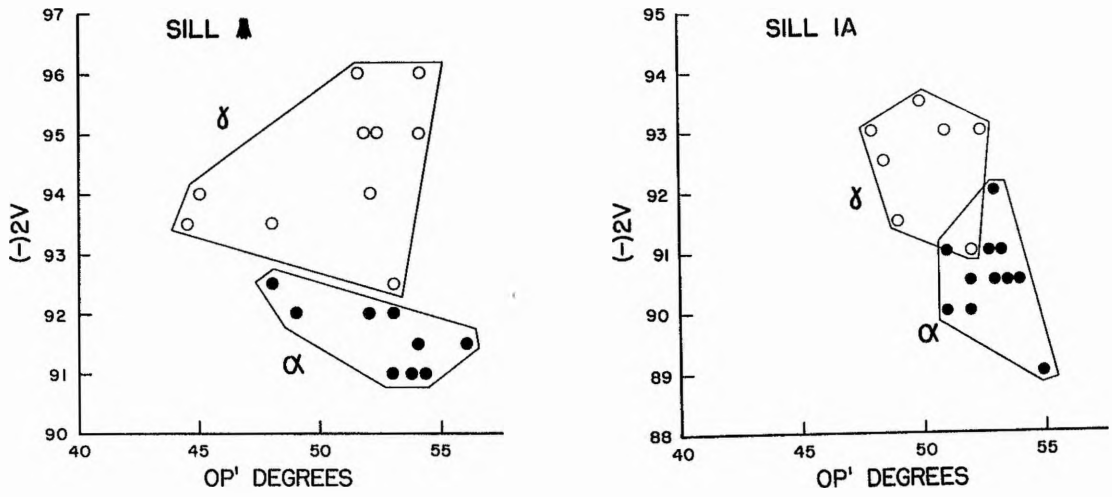
The compositions of the olivines were estimated from the optical data collated by Poldervaart (1950). The molecular percentages of fayalite only are given below. In Sill 1, the average values of (-)2V for groups (A), (B), (C) respectively correspond to: Fa_7, $Fa_{7.5}$, and Fa_8. Agreement is excellent. In group (A) the mean values for $(-)2V_\alpha$ and $(-)2V_\gamma$ give the compositions $Fa_{9.5}$ and $Fa_{3.5}$, so the discrepancy between the measurements over different bisectrices amounts to 2.9°, corresponding to 6 per cent fayalite.

In Sill 1A, the average values of (-)2V for the three groups of measurements give the same composition, namely Fa_{10}. In group (A) the mean values for $(-)2V_\alpha$ and $(-)2V_\gamma$ give the compositions Fa_{12} and Fa_8. The discrepancy between the measurements about different bisectrices amounts to 2.0°, corresponding to 4 per cent fayalite. This is smaller than in Sill 1.

Equal values for 2H were found at the centre and margin of each large crystal measured, and the occurrence of zoning was not confirmed. This may indicate compositional differences among the olivines within each sill but the low values of the errors for the means of 2V measurements indicate that such differences, if present, are too small to be distinguished. It is possible that olivine crystallizing from a high

TABLE 16. DIFFERENCES BETWEEN THE MEANS OF (-)2V MEASURED OVER α AND γ

	SILL 1			SILL 1A		
OBSERVED DIFFERENCE BETWEEN MEANS	2.9	1.3	1.1	2.0	0.1	0.0
STANDARD ERROR OF THE DIFFERENCE	0.4047	0.6799	0.5120	0.4139	0.9536	1.031



a. b.

Figure 24. Measurements of (-)2V obtained by method (A) plotted against the greatest radial angle OP' (see figure 23a) involved in the measurement. The results are taken from tables 13 and 14. In both sills, the measurements about α are separated from those about γ.

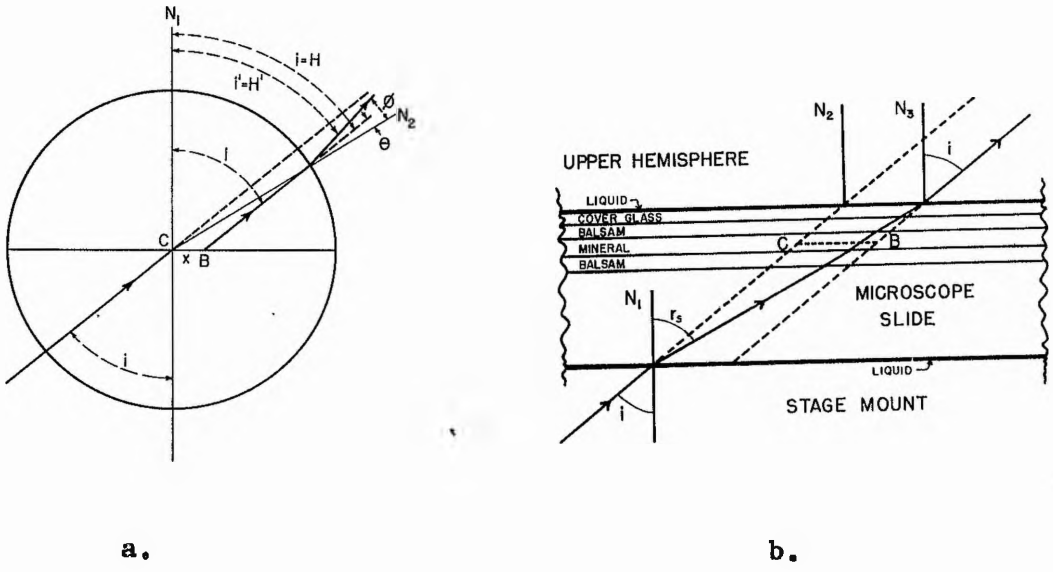
temperature ultrabasic liquid may contain more calcium orthosilicate in solid solution than is usually present in basaltic olivines (see Part III), but the effect of calcium orthosilicate on the optics of the forsterite-fayalite series is not known.

In each sill the averages of (-)2V obtained by each of the three methods agree within 1^{o}, and the greatest differences between the means of measurements about α and γ are found in columns (A) of table 15. Yet the latter results were obtained by a more accurate method than those in columns (B) and (C). The significance of these differences may be tested statistically. The variance of the difference between two independent random variables is equal to the sum of their variances (Moroney 1951, p. 220), and the standard deviation of the variables is the square root of the variance. Considering the arithmetic means obtained by the different methods as independent variables, the standard errors of the differences of means obtained by measurements over α and γ have been calculated and are compared with the observed differences in table 16. A difference of more than two standard errors between means is probably significant and a difference of more than three standard errors between the means is highly significant; the probability that such a difference should arise by chance is less than one half of one per cent. The observed differences between the means obtained by method (A), in both sills, are more than four times the standard errors of the differences and it is very improbable that they are due to chance. In Sill 1A, by methods (B) and (C) it is obvious that the differences are not significant. In Sill 1, the differences obtained in methods (B) and (C) are about two standard errors and they may be significant. The values for group (A) are plotted in figure 24 against the greatest

radial angle involved in the measurement. A statistical test is hardly necessary to prove that a significant difference exists.

This confirms that the means of supposedly less accurate single axis measurements give more consistent results for the same grains than do the means of the conoscopic double axis measurements. The results in columns (B) were obtained from measurements which involved smaller angles of tilt of the universal stage than those in columns (A), as were those in columns (C), obtained for different grains. The average values must be considered as the best values and thus, for higher angles of tilt of the stage $(-)2V_{\alpha}$ is smaller and $(-)2V_{\gamma}$ is greater than the expected value. Since $(-)2V_{\gamma}$ is the supplement of $(+)2V_{\gamma}$ it is clear that for higher angles of tilt of the stage (method A) both the measured angles $2H_{\alpha}$ and $2H_{\gamma}$ are smaller than the mean value of 2H obtained when lower angles of tilt are involved (methods B and C). The value of 2H within the upper hemisphere depends upon the refractive index of the hemispheres, n, 2V and β, all of which are fixed quantities in a given measurement. Therefore, for large tilts of the stage, the observed angle between the optic axes is smaller than the true 2H, i.e. the angle between the rays in the upper hemisphere. This means that there must be refraction at the surface of the upper hemisphere and the emergent ray cannot be normal to the surface. Since the emergent angle H' is smaller than the true angle H the light rays must be displaced from the centre of the sphere as illustrated diagrammatically in figure 25a, and it is in the centre of the sphere that the cause of the observed discrepancy must have its origin.

The theoretical treatment of the universal stage as a uniform sphere with a thin mineral plate at its centre is, of course, simplified and



a. b.

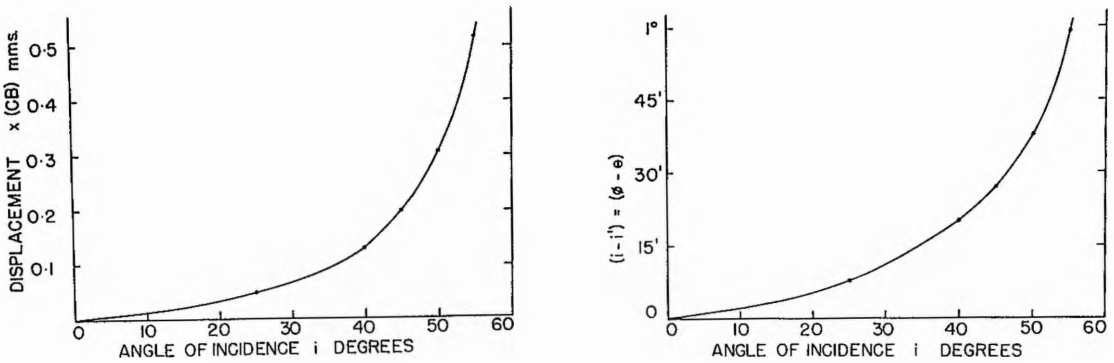
Figure 25. a. Diagrammatic representation of the path of a light ray through the universal stage. The angle of incidence is $\underline{i}$ = H, and the emergent angle, $\underline{i}'$ = H' is smaller than $\underline{i}$ (see text). The emergent ray, therefore, is not normal to the glass-air interface of the upper hemisphere, and there must be a displacement CB = $\underline{x}$ in the central layers of the sphere.
b. Diagrammatic representation of the seven layers at the centre of the universal stage, between the stage mount and the upper hemisphere. The centre of the sphere is at the centre of the mineral plate, C. $\underline{r_s}$ is the angle of refraction within the microscopic slide, and the distance CB is the displacement of the light ray indicated in figure 25a. N_1, N_2 and N_3 are normals.

with increasing angles of tilt the treatment becomes less rigorous. When a thin section is mounted on the stage there are seven refracting layers between the stage glass and the upper hemisphere and their effect upon the light rays cannot be neglected for high angles of tilt. The paths of light rays have been traced through the layers for varying angles of tilt of the stage in an attempt to find the cause of the deduced displacement CB, figure 25a.

Consider a light ray with angle of incidence i passing through the mount in such a way that without refraction it would pass through the centre C of the sphere, i.e. the centre of the mineral plate if the stage is correctly adjusted, figure 25b. In each layer, the light ray will have an angle of refraction r, and $r > i$ for all layers except the mineral plate which, in this example, has a refractive index greater than that of the sphere. In a given layer of thickness t, the ray will be displaced laterally by a distance $\Delta x = t(\tan r - \tan i)$. The total displacement of the ray in passing through the seven layers will be $x = \Sigma t(\tan r - \tan i)$, and this corresponds to CB in figure 25. The thickness of the microscope slide is large compared to the other layers and $x = t_s(\tan r_s - \tan i)$ approximately, where t_s and r_s are the thickness of and the angle of refraction in the glass slide. Knowing that the refractive index of the slide is 1.516 and $t_s = 1$ mm., values of x have been calculated for different values of i (figure 26a). From the angles of incidence and the calculated values of x approximate values of θ, the angle of incidence of the emergent ray at the glass-air interface of the upper hemisphere (of radius 12 mm.), are given by the expression:-

$\theta = \frac{180.x.\cos i}{(12 - x\sin i)}$ degrees (see figure 25a). The angle of emergence is $\phi = \sin^{-1}(1.649\sin\theta)$ and from figure 25a it can be seen that the error of an angular measurement, for an angle of tilt (angle of incidence) i, is $(i - i') = (\phi - \theta)$. Calculated values of $(\phi - \theta)$ have been plotted against i in figure 26b, and for a given angle of tilt the observed angle i' will be smaller than the true angle i by an amount which can be read directly from the graph.

When the radial angle from the azimuth of the sphere to a point of measurement is 35°, the calculated error of measurement $(i - i')$ is 0.25°.



a. b.

Figure 26. a. The calculated displacement CB (figure 25) plotted against the angle of incidence i.
b. The calculated angular error (i - i') plotted against the angle of incidence i.
There is a rapid rate of increase of both values when i exceeds 40°.

For angles less than 35°, the error is negligible but for angles greater than 35° it increases markedly, passing through 0.5° for an angle of tilt of 46° and reaching 1° for an angle of tilt of 56°. These errors are much increased when allowance is made also for the displacive effect of the stage mount. It is tacitly assumed in text books that the stage glass has the same refractive index as the hemispheres, but this is not so. The stage glass used in the present measurements has refractive index 1.560 and thickness 2.46 mm. (measured by R. Johnston). If the displacive effect of this plate is added to that of the microscope slide, a ray with angle of incidence 45° would have an error of $(\phi - \theta) = 2^\circ$ when it emerged from the sphere instead of the 27' produced by the microscope slide alone (figure 26b).

Examination of the path of a single light ray demonstrates an increasing error with increasing tilt of the stage, but it does not give

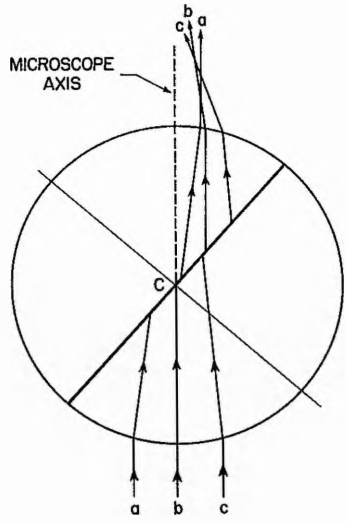


Figure 27. Diagrammatic representation of the refraction and displacement of a beam of parallel rays entering the universal stage with a high angle of tilt. The centre ray b is directed towards the centre of the sphere, C. The outer rays of the beam are refracted slightly on entering the sphere. The beam as a whole is displaced within the central layers of the sphere (figure 25) and the effective displacement of rays in different parts of the beam varies. In the example shown, the ray a is displaced the least, and this ray emerges nearly parallel to the microscope axis. The rays b and c are refracted through successively greater angles on emergence. The angle measured is the angle of tilt, i.e. the angle of incidence of the central ray b. The rays observed will be those most nearly parallel to the microscope axis, i.e. those near a. The ray a has a different angle within the hemispheres compared to that of b.

a realistic picture of what actually happens when a measurement is made. Figure 27 shows a beam of parallel light rays, abc, entering the sphere. Only those rays which emerge almost parallel to the incident beam will reach the eye of the observer. The ray b which is directed towards the centre of the sphere is incident normally but the other rays are slightly refracted on entering the sphere, the degree of refraction increasing

towards the edges of the beam, a and c. The beam as a whole is displaced by refraction within the central layers. Each ray within the beam has a different effective displacement from the centre of the sphere and each ray therefore has a different error ($\phi - \theta$). The rays in the side c of the beam will have a value of ($\phi - \theta$) greater than, and rays in the side a of the beam less than that for the centre of the beam, b. Figure 27 shows that, except for low angles of tilt, the rays entering the microscope cannot be those directed towards the centre of the sphere, i.e. those in the centre of the beam near b. The rays entering the microscope are those from the side a of the incident beam. These rays are refracted when they enter the sphere and their angles within the hemispheres do not equal the angle of incidence, which is the measured angle. With increasing angle of tilt, rays further from the centre of the incident beam are received by the microscope and the difference between the recorded angle (angle of incidence) and the true angle (angle of the ray within the hemispheres) also increases. This is a direct result of the increasing displacement within the central layers of the sphere, and it is clear that accurate universal stage measurements cannot be expected when high angles of tilt are involved unless a correction is made for the displacement within the central layers as well as for refraction within the mineral plate.

Conclusions

(1) No significant difference was found between single axis measurements made over different bisectrices in Sill 1A. In Sill 1, the differences are of the order of the experimental errors, and they may be significant statistically. The means of single axis measurements

are in close agreement with the means of double axis measurements.

(2) In double axis measurements a significant difference exists between measurements made over different bisectrices. The average of the means of measurements over α and over γ are in close agreement with the single axis measurements.

(3) The discrepancy in the double axis measurements may be explained if the observed angle is smaller than the true angle and it has been shown that refraction within the microscope slide and stage mount could produce this effect.

These conclusions are not in accord with those of Game (1941) and Frankel (1942). The difference between the means of $2V_{\alpha}$ and $2V_{\gamma}$ is of the same order as that noted by Johnston (1953). Wilkinson (1956) found good agreement between double axis and single axis measurements and this is probably due to the fact that he avoided double axis measurements involving high angles of rotation.

The results here presented emphasize the importance of using low angles of tilt of the universal stage whenever possible and they demonstrate the nature and magnitude of the error introduced when high angles cannot be avoided. The introduction of errors with high angles of tilt has frequently been noted in the literature. Turner (1942a) discussed refractive index corrections and stated that the errors cannot wholly be eliminated if high angles are involved, but according to Hallimond and Taylor (1950) little or nothing has been said in most text books about the refractive effect of the glass-air interface of the hemisphere. The only quantitative treatment of errors known to the writer is that by Piller (1957), who discusses the measuring error which occurs when the specimen or coverglass is of the wrong thickness, causing

a vertical displacement of the upper hemisphere with reference to the horizontal axis.

High angles of tilt of the universal stage, although avoided whenever possible, must frequently be used in optical studies. This is particularly true for the double axis determination of optic axial angles near 90°. By using the double axis conoscopic method in order to obtain results of high accuracy, a further error is introduced and this can be detected only because the method is so accurate for a given measurement; the difference between $(-)2V_{\alpha}$ and $(-)2V_{\gamma}$ is the only indication that such an error exists. If one measurement made about α or γ were assumed correct the result could easily be wrong by more than 2°, corresponding to an error of at least 4 molecular per cent in the composition of an olivine (see figure 24). The accuracy of such measurements is therefore not as high as claimed by Hallimond (1950) unless corrections are made for the high angles of tilt.

Fairbairn and Podolsky (1951) stressed the importance of precision and accuracy in stage measurements and regretted the dearth of published data on the subject. They recorded the compositional variation occurring among plagioclase feldspar within the same rock and concluded that unless accurate determinations are made such variations may not be distinguished. Yet the supposedly accurate measurements plotted in figure 24, with estimated experimental errors of $\pm 0.5^{\circ}$, occupy ranges of 5°. This could be interpreted as due to compositional variations among the olivines, amounting to about 10 molecular per cent of fayalite, but the systematization of results indicates that it is due to additional errors produced by the high angles of tilt which had to be used. To the request of Fairbairn and Podolsky (1951) for greater precision of measurement may be added a plea for further investigation of the errors involved in measurements.

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